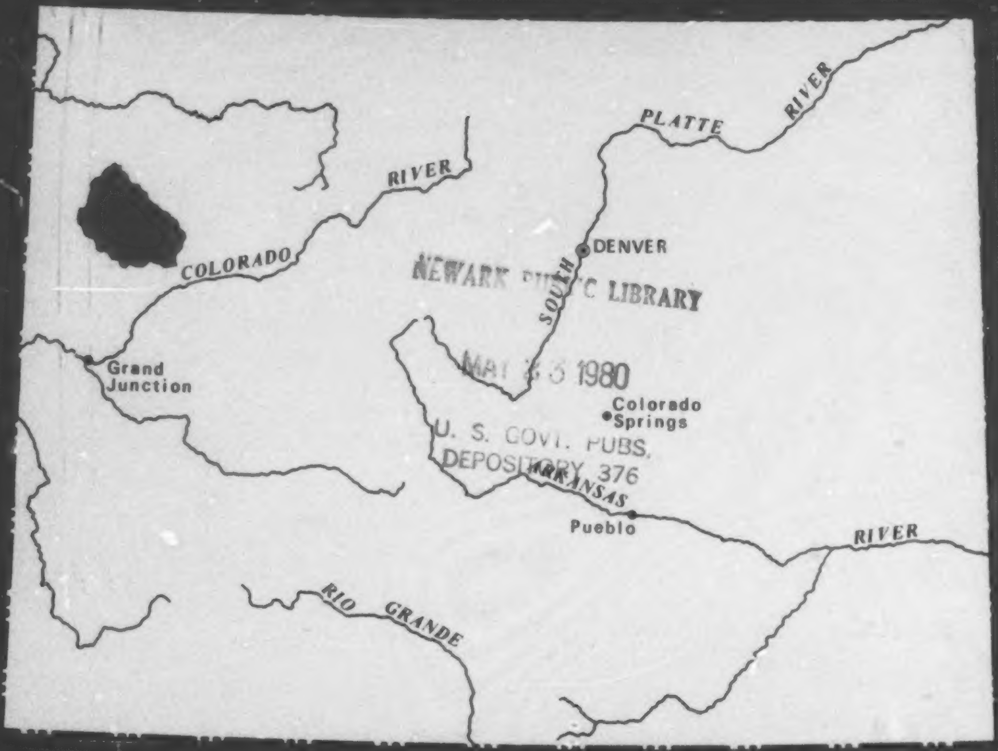
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HYDROGEOCHEMISTRY AND SIMULATED SOLUTE TRANSPORT, PICEANCE BASIN, NORTHWESTERN COLORADO

By Stanley G. Robson and George J. Saulnier, Jr.

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Prepared in cooperation with the
U.S. Environmental Protection Agency

Lakewood, Colorado

April 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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METRIC CONVERSION FACTORS

For the reader who may prefer to use metric units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound units	*By*	*To obtain metric units*
acre	$4.047\text{x}10^{-1}$	hectare
acre-foot (acre-ft)	$1.234\text{x}10^{-3}$	cubic hectometer
barrel	$1.59\text{x}10^{1}$	cubic meter
foot (ft)	$3.048\text{x}10^{-1}$	meter
foot per day (ft/d)	$3.048\text{x}10^{-1}$	meter per day
foot per mile (ft/mi)	$1.894\text{x}10^{-1}$	meter per kilometer
cubic foot per second (ft^3/s)	$2.832\text{x}10^{-2}$	cubic meter per second
foot per year(ft/yr)	$3.048\text{x}10^{-1}$	meter per year
gallon per ton (gal/ton)	$4.171\text{x}10^{-2}$	cubic meter per megagram
square inch per pound (in^2/lb)	$1.450\text{x}10^{-1}$	kilopascal^{-1}
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
pound per day (lb/d)	$4.536\text{x}10^{-1}$	kilogram per day
pound per day per square mile [(lb/d)/mi^2]	$1.751\text{x}10^{-1}$	kilogram per day per square kilometer
pound per square inch (lb/in^2)	6.895	kilopascal
ton, short	$9.072\text{x}10^{-1}$	metric ton

HYDROGEOCHEMISTRY AND SIMULATED SOLUTE TRANSPORT, PICEANCE BASIN, NORTHWESTERN COLORADO

By Stanley G. Robson and George J. Saulnier, Jr.

ABSTRACT

The Piceance basin of northwestern Colorado contains rich deposits of oil shale in sedimentary rocks of the Parachute Creek Member of the Green River Formation. Plans for mining these deposits in Federal prototype lease tracts C-a and C-b require ground water to be pumped to allow the construction of underground retorts for use in extracting the shale oil. The possible adverse effects of mine pumping and resaturation of spent shale in an abandoned mine were investigated by studying the geochemistry of the aquifers and by use of ground-water quality modeling techniques.

The aquifers in the basin crop out along the east, north, and west margins of the basin and attain a saturated thickness of 2,000 feet in the northeast part of the basin. Faults, joints, collapse breccia, and solution cavities are the primary source of permeability in the otherwise impermeable sandstone and marlstone sedimentary rocks. Estimates of the lateral hydraulic conductivity of the aquifers range from 0.1 to 2.0 feet per day and of the vertical hydraulic conductivity from 7×10^{-4} to 1.0 foot per day, respectively.

Ground-water recharge occurs from infiltration of precipitation in the upland areas along the east, south, and west margins of the basin. From the recharge areas, ground water moves vertically into deeper zones in the aquifers and laterally toward the discharge areas along Piceance and Yellow Creeks and their tributaries. The steady-state recharge-discharge rate of 32 cubic feet per second results in hydraulic gradients in the aquifers of as much as 130 feet per mile in some parts of the basin.

The saline zone, located at the base of the Parachute Creek Member, contains the soluble minerals nahcolite and halite and is the primary source of the dissolved solids in the ground water. Dissolution of minerals in the unsaturated zone and in the aquifers also contribute dissolved solids to the water. Additional chemical reactions occurring in the aquifers include precipitation, ion-exchange, and oxidation-reduction reactions. The product of the principal chemical reactions is a sodium bicarbonate water with oxidized sulfur species in the Uinta Formation and reduced sulfur species in the Parachute Creek Member.

Carbonate species are produced primarily by reduction of sulfur species and dissolution of the carbonate minerals calcite, dolomite, and nahcolite. Carbonate species are removed from the system in the northern part of the basin by calcite precipitation. Relatively large sodium concentrations are produced by ion exchange and nahcolite and halite dissolution. Local brines are produced where faults expose saline minerals to circulating ground water.

A mathematical model was used to simulate the ground-water quality changes that would occur as a result of mine dewatering or leaching of saline minerals from an abandoned mine. The model simulates confined density-dependent flow and solute transport in three dimensions with dispersion in nonhomogeneous, anisotropic aquifers under steady or transient ground-water flow conditions. An acceptable model calibration was achieved for steady-state flow conditions.

Simulations of pumping mines in tracts C-a and C-b indicate that the altered direction of ground-water movement near the pumped mines will decrease dissolved-solids concentrations in ground water near the mines and increase dissolved-solids concentrations in some areas downgradient from the mines. Simulated long-term pumping from tract C-a at a rate of 5 cubic feet per second indicates that ground-water discharge to Yellow Creek will be reduced by as much as 2 cubic feet per second and to Piceance Creek by as much as 3 cubic feet per second. Simulated long-term pumping from tract C-b at 15 cubic feet per second indicates that ground-water discharge to Piceance Creek will be reduced by as much as 15 cubic feet per second and dissolved-solids concentration in the creek will be increased by as much as 300 milligrams per liter.

Leaching of saline minerals contained in spent shale in an abandoned and flooded mine could have an adverse affect on the surface- and ground-water quality in the basin. Model simulations of mine leaching in tract C-a indicate that the dissolved-solids concentration of ground water in a 140-square mile area downgradient from the tract would be increased by more than 10 milligrams per liter after 60 years of leaching. Dissolved-solids concentrations as much as 40,000 milligrams per liter were produced adjacent to the simulated mine. After 60 years of leaching, the water quality in Yellow Creek had not yet been adversely affected by the degraded quality of the ground water. Simulations of mine leaching at tract C-b indicate that the dissolved-solids concentration in a 40-square mile area near the tract would be increased by more than 10 milligrams per liter after 60 years of leaching. The estimated dissolved-solids concentration in Piceance Creek increased from 750 to 1,750 milligrams per liter in a reach of the creek near tract C-b. Modeling thus indicates that equal rates of mine leaching from tracts C-a and C-b will produce much different effects on the water quality in the Piceance basin. Tract C-a, by virtue of its remote location from perennial streams, will primarily degrade the ground-water quality over a large area to the northeast of the tract. Tract C-b, by contrast, will primarily degrade the surface-water quality in Piceance Creek with only localized effects on the ground-water quality.

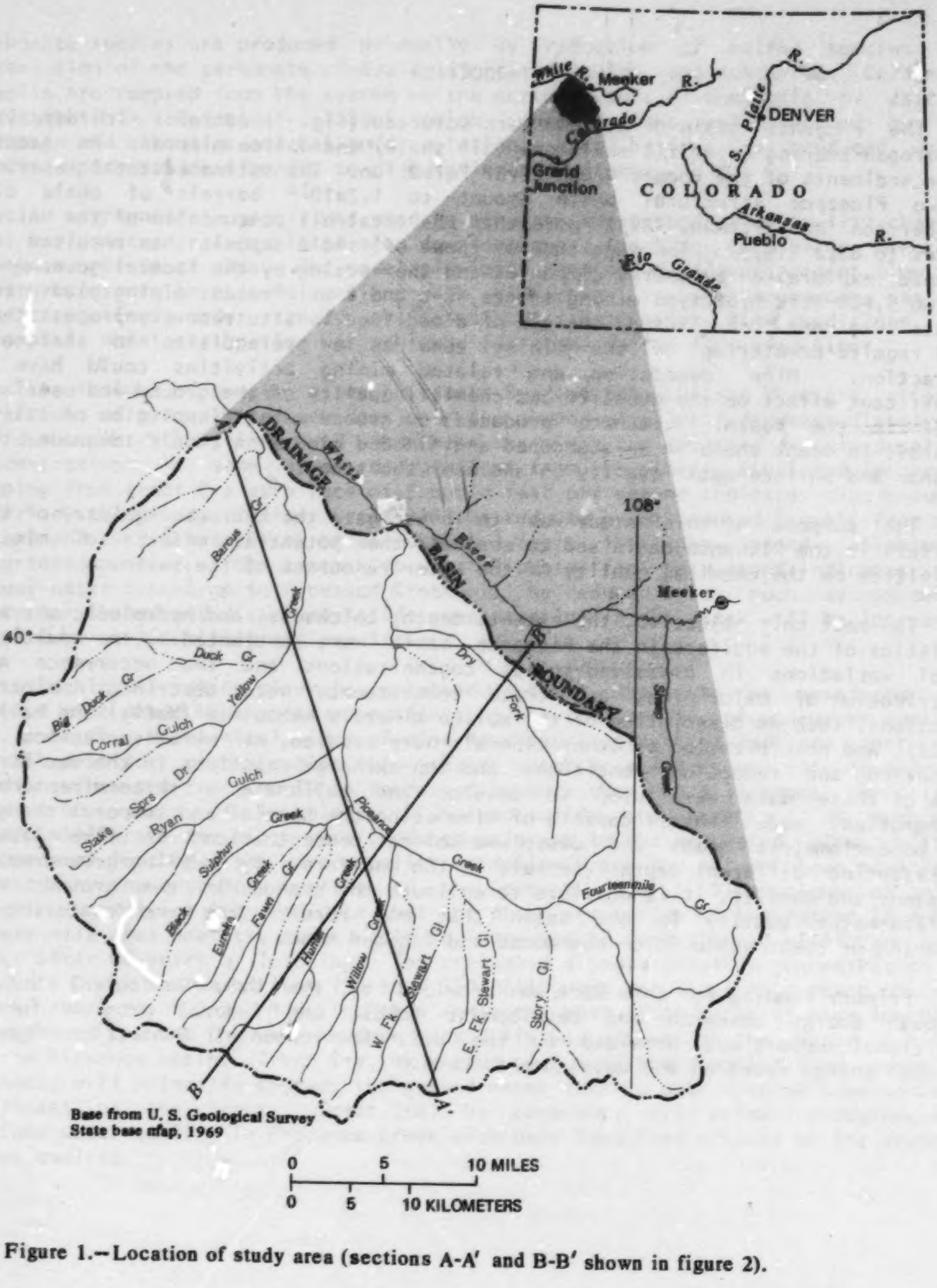
INTRODUCTION

The Piceance basin of northwestern Colorado (fig. 1) contains rich deposits of kerogen-bearing dolomitic marlstone (oil shale) and saline minerals in lacustrine sediments of the Eocene Green River Formation. The estimated total reserves of the Piceance structural basin amount to 1.2×10^{12} barrels of shale oil (Culbertson and Pitman, 1973)--more than the total oil consumption of the United States to date (1979). The magnitude of these oil-shale deposits has resulted in intense exploration by energy companies and the leasing by the Federal government of two 5,000-acre prototype mining tracts, C-a and C-b. Present mining plans for tracts C-a and C-b include the use of a modified in-situ recovery process that will require dewatering of the mining zone as a prerequisite to shale-oil extraction. Mine dewatering and related mining activities could have a significant affect on the quantity and chemical quality of the ground and surface water in the basin. Leachate produced by ground-water dissolution of saline minerals in spent shale in an abandoned and flooded mine also could degrade the ground- and surface-water quality on and near the tracts.

The purpose of this study was to investigate the hydrogeochemistry of the aquifers in the Piceance basin and to evaluate the potential effects of mining activities on the chemical quality of the water resources of the basin.

To meet this objective, the extent, depth, thickness, and hydrologic characteristics of the aquifers in the Piceance basin were estimated. In addition, areal variations in dissolved-solids concentrations and the occurrence and distribution of major ions and trace constituents were described. Mineral reactions, such as dissolution of the saline minerals nahcolite ($NaCO_3$) and halite ($NaCl$), and precipitation of other minerals were studied, as were variations in oxidation and reduction conditions and ion-exchange reactions in the aquifers. Some of these data were used to develop and calibrate a three-dimensional mathematical model that is capable of simulating the spatial and temporal changes in potentiometric heads and dissolved-solids concentrations in five layers representing different depth intervals in the aquifers. By modeling ground-water movement and quality, it is possible to estimate the changes in the ground- and surface-water quality in the basin that may result from mine dewatering or leaching of spent shale in an abandoned and flooded mine.

Primary funding for this work was provided by the U.S. Geological Survey through energy research and development funds, and Federal program funds. Additional support was provided by the U.S. Environmental Protection Agency through energy research and development funds.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Meeker
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DENVER
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Grand Junction
COLORADO
Arkansas
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Pueblo
Rio Grande
A'
DRAINAGE
White
River
BASIN
BOUNDARY
108°
Meeker
40°
Barcus Cr
Yellow
Creek
Duck Cr
Big Duck Cr
Corral Gulch
Stake Sprs Dr
Ryan Gulch
Greek
Piceance
Dry Fork
Sulphur
Black
Eureka Creek
Fawn Cr
Hunter Creek
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W. Fk Stewart Gl
E. Fk Stewart Gl
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0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

Figure 1.—Location of study area (sections A-A′ and B-B′ shown in figure 2).

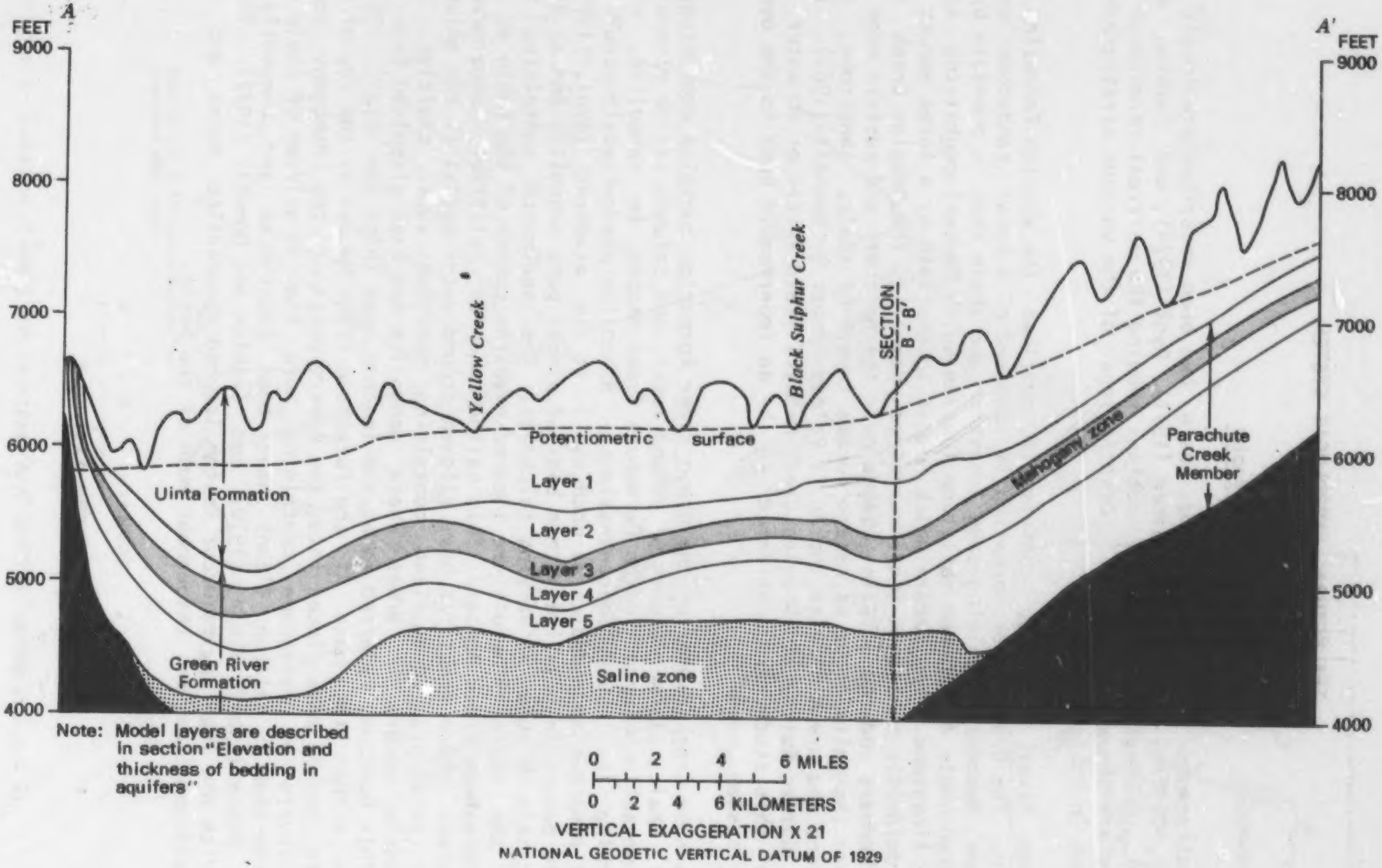
THE NATURAL HYDROLOGIC SYSTEM

Stratigraphy

The stratigraphy of the Piceance basin has been described previously by Donnell (1961), Coffin, Welder and Glanzman (1971), Dyni (1974), and Cashion and Donnell (1974). Generalized geologic sections showing the vertical relationships of these units are shown in figure 2. Descriptions of the various stratigraphic units are given in table 1.

The Green River Formation conformably overlies the Wasatch Formation in Piceance basin. The Green River Formation is composed of a basal sandstone unit (Douglas Creek Member) containing some limestone and shale that is overlain by a finely laminated shale and barren marlstone (Garden Gulch Member) containing some sandstone and limestone. The Garden Gulch Member is overlain by a large amount of kerogen-rich dolomitic marlstone (Parachute Creek Member). The Douglas Creek and Garden Gulch Members undergo a facies change near the northern and eastern edge of the basin where the units occur as heterogeneous layers of shale, sandstone, and barren marlstone and are mapped as the Anvil Points Member by Donnell (1961). The Anvil Points, Garden Gulch, and Douglas Creek Members yield little or no water to wells and, in this study, are considered to be an impermeable base to the overlying aquifer system.

The Parachute Creek Member of the Green River Formation contains economically valuable oil shale, large volumes of ground water, and soluble saline minerals. The most common saline mineral in the Parachute Creek Member is nahcolite, with halite occurring in lesser concentrations. Nahcolite predominately occurs as large crystal rosettes and nodules as much as 3 ft in diameter (Dyni, 1974). Nahcolite also occurs in relatively thin beds of almost pure nahcolite and as disseminated crystals in zones of varying thickness. The sediments containing the majority of the saline minerals are located near the center of the basin at the base of the Parachute Creek Member. This saline zone is relatively impermeable except in areas where fractures have allowed ground water access to the soluble minerals. A stratigraphic horizon containing numerous vugs, cavities, and collapse breccia occurs in areas where nahcolite has been dissolved from the formation. This horizon, referred to as the leached zone (Hite and Dyni, 1967), extends from either the base of the Parachute Creek Member or the top of the saline zone to, and in some places into, the lower part of the Mahogany zone. Alternating layers of marlstone containing more than 30 gal/ton of shale oil (rich) and less than 15 gal/ton (lean) have been identified and sequentially numbered by Donnell and Blair (1970) and Cashion and Donnell (1972). These alternating rich and lean layers occur in the leached and saline zones and are used as stratigraphic markers throughout much of the basin.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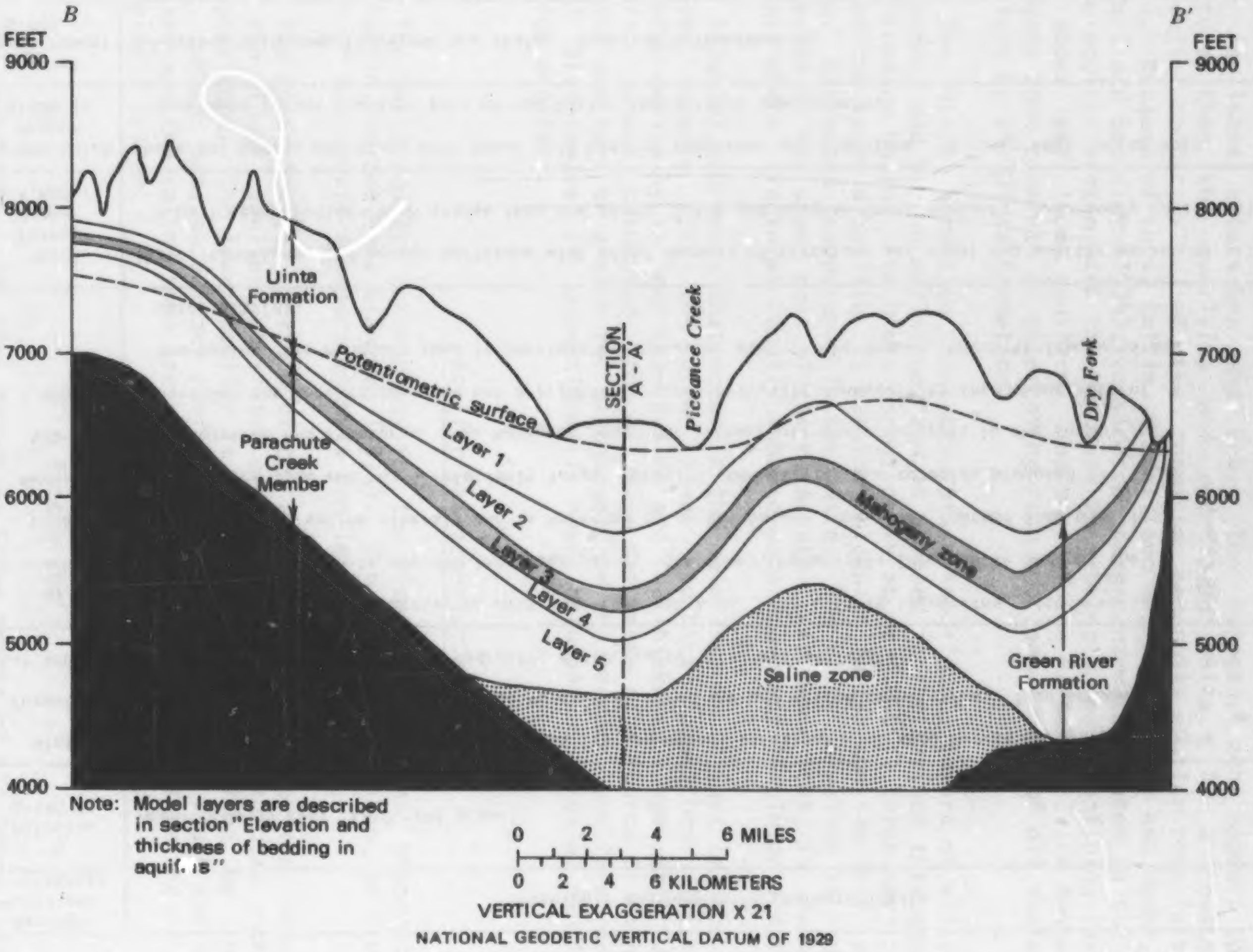
4000
Yellow Creek
Black Sulphur Creek
SECTION B - B'
Potentiometric surface
Uinta Formation
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Mahogany zone
Parachute Creek Member
Green River Formation
Saline zone
0 2 4 6 MILES
0 2 4 6 KILOMETERS
VERTICAL EXAGGERATION X 21
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Note: Model layers are described in section "Elevation and thickness of bedding in aquifers"

Figure 2.—Generalized geologic sections through the Piceance basin (trace of sections located on figure 1).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7000
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5000
4000
Uinta Formation
Parachute Creek Member
Potentiometric surface
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
SECTION A - A′
Piceance Creek
Dry Fork
Mahogany zone
Saline zone
Green River Formation
0 2 4 6 MILES
0 2 4 6 KILOMETERS
VERTICAL EXAGGERATION X 21
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Note: Model layers are described in section "Elevation and thickness of bedding in aquif. rs"

Figure 2.—Generalized geologic sections through the Piceance basin (trace of sections located on figure 1) --Continued.

Table 1.--*Stratigraphic units in Piceance basin*

[Modified from Coffin, Welder, and Glanzman, 1971]

Geologic age	Geologic unit and thickness		Lithologic and hydraulic characteristics
Holocene and Pleistocene	Alluvium 0-140 ft		Heterogeneous clay, sand, and gravel.
Eocene	Uinta Formation 0-1,400 ft		Coarse- to fine-grained, poorly sorted, silty sandstone, siltstone with some barren marlstone. Little or no primary porosity remains due to calcium carbonate and silica cementation. Some secondary porosity due to fractures. Hydraulic conductivity is relatively small.
	Green River Formation	Parachute Creek Member 500-1,400 ft	Kerogenaceous dolomitic marlstone with some thin ash beds. The unit is lacustrine, with a varved appearance and can be divided into four parts. The lower, relatively impermeable part of the unit contains saline minerals and is referred to as the saline zone. The leached zone overlies the saline zone and has a relatively large hydraulic conductivity due to voids produced by dissolution and fractures. The Mahogany zone, the richest oil-shale interval in the section, overlies the leached zone and has a relatively small hydraulic conductivity throughout most of the basin. The Mahogany zone is overlain by the upper part of the member, which is fractured and water-bearing.
		Anvil Points Member 0-1,800 ft	Shale, sandstone, and barren marlstone with minor amounts of siltstone and algal and oolitic marlstone. A basin-edge facies which grades into the Garden Gulch and Douglas Creek Members. Relatively impermeable.
		Garden Gulch Member 0-900 ft	Shale and barren marlstone with local thin beds of sandstone and limestone. A basin-edge facies best developed in the southern part of the basin. Relatively impermeable.
		Douglas Creek Member 0-800 ft	Sandstone with some limestone and shale. Relatively impermeable.

The Mahogany zone is the most consistently rich and areally extensive interval of oil shale in the Piceance basin, being correlated in outcrops and electric logs throughout the basin. The Mahogany zone is located in the upper one-third of the Parachute Creek Member and is considered the principal mining zone in lease tracts C-a and C-b. The Mahogany zone appears to have fewer fractures than the overlying and underlying units. As a consequence, the hydraulic conductivity of the zone is generally smaller than in the adjacent units. Because of this, Coffin, Welder, and Glanzman (1971) and Weeks, Leavesley, Welder, and Saulnier (1974), considered the ground-water system in the basin to be a two-aquifer system with the Mahogany zone being a leaky confining layer between the upper and lower aquifers. The part of the Parachute Creek Member above the Mahogany zone consists of alternating rich and lean layers of oil shale that are overlain by the Uinta Formation.

The Uinta Formation consists of discontinuous layers of silty sandstone, siltstone, and barren marlstone, and is exposed at the surface throughout much of the Piceance basin. The Uinta Formation is about 1,400 ft thick near the northern end of the study area (fig. 2) but the thickness varies considerably due to the steep, dissected topography in the basin. The Uinta Formation is hydrologically connected to the upper part of the Parachute Creek Member but is less permeable except where fractures locally enhance water movement (Saulnier and Ford, 1977).

Alluvial sediments that occur in the major stream valleys in the basin are derived locally from the Green River and Uinta Formations. The width of the alluvium generally is less than 0.5 mi and the thickness ranges from 0 to about 140 ft. Where saturated, the alluvium can serve as a source of recharge to the bedrock aquifers or a sink for discharge from the bedrock aquifers depending on local differences in potentiometric heads between the alluvial aquifers and the bedrock aquifers.

Aquifer Characteristics

The basic aquifer terminology for the Piceance basin was proposed initially by Coffin, Welder, and Glanzman (1971). The hydrologic system, as proposed, consists of two aquifers separated by a confining layer.

The upper aquifer consists of the saturated rocks above the Mahogany zone, and the lower aquifer consists of the permeable, saturated rocks below the Mahogany zone. The lower aquifer is considered to be confined by the Mahogany zone, which acts as a leaky confining layer. The Douglas Creek and Garden Gulch Members and the saline zone are relatively impermeable and form the base of this hydrologic system.

Fracturing

The marlstones in the Parachute Creek Member of the Green River Formation have little or no primary porosity. Wide variations in hydraulic properties exist over short distances because fractures, solution cavities, and collapse breccia are the main source of secondary porosity and permeability (Weeks and others, 1974). The lean marlstones are more brittle than the rich marlstones and, thus, tend to be more fractured and more permeable than the rich units. Onsite observations indicate that vertical fractures may be confined to particular beds or layers, or may pass vertically through many beds or layers. The primary direction of fracturing is approximately west northwest, as indicated by the mapped surficial fracturing in the area (fig. 3) and by the work of Wolff, Bredehoeft, Keys, and Shuter (1974). Onsite observations by G. J. Saulnier and the work of Welder (1971) indicate the existence of an extensive network of surficial joints and minor faults subordinate to the major faults in the area. The alinement of individual fractures varies from normal to subparallel to the strike of the major faults (fig. 3). The fracture permeability that occurs in wells located away from the major fault zones indicates that joints and minor faults may occur at depth in a pattern analogous to that indicated at the surface.

The alinement of the major fracture systems is similar to the alinement of the structural trough at the base of the leached zone and the alinement of the surface-water drainage system. The tectonic activity that shaped the Piceance basin may have affected the distribution of fracture permeability in the bedrock aquifers and predisposed the surface-water drainage system to erode channels either along, or perpendicular to, the structure and major fracture alinement.

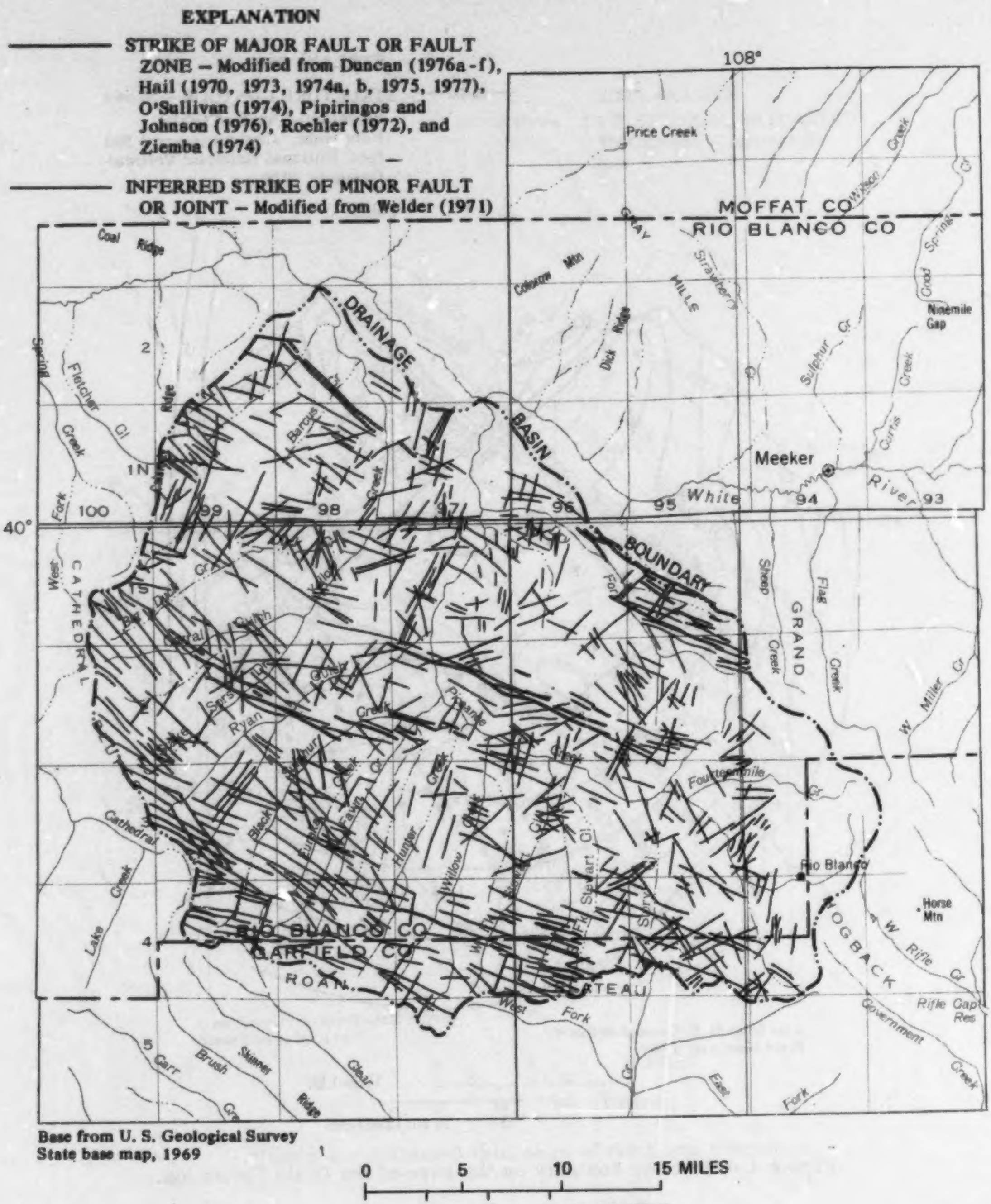
Aquifer Limits

The aquifer system is truncated by topography on the eastern, northern, and western margins of the basin where the water-bearing units crop out. The southern boundary of the study area coincides with a ground-water divide extending along the Roan Plateau to Cathedral Bluffs (Coffin and others, 1971). South of this divide ground water flows toward the Colorado River. North of this divide, ground water flows toward Piceance and Yellow Creeks, the two major streams draining the study area. The lateral extent of the aquifers considered in this study coincides with the area studied by Weeks, Leavesley, Welder, and Saulnier (1974).

Elevation and Thickness of Bedding in Aquifers

The vertical variations in potentiometric head and ground-water quality that occur in Piceance basin prompted the authors to use a five-layer system to describe the hydrology and geochemistry (fig. 2). Each of the layers was subsequently represented as a layer in a mathematical model of the ground-water system.

Layer 1 consists of the saturated part of the Uinta Formation. The base of layer 1 slopes toward the northwestern part of the basin and ranges in elevation from about 5,500 to about 8,000 ft (fig. 4). The saturated thickness of layer 1 exceeds 800 ft in the northwestern part of the basin and diminishes to 0 around a structural high between Piceance Creek and Dry Fork, and around the basin margins (fig. 5).



EXPLANATION

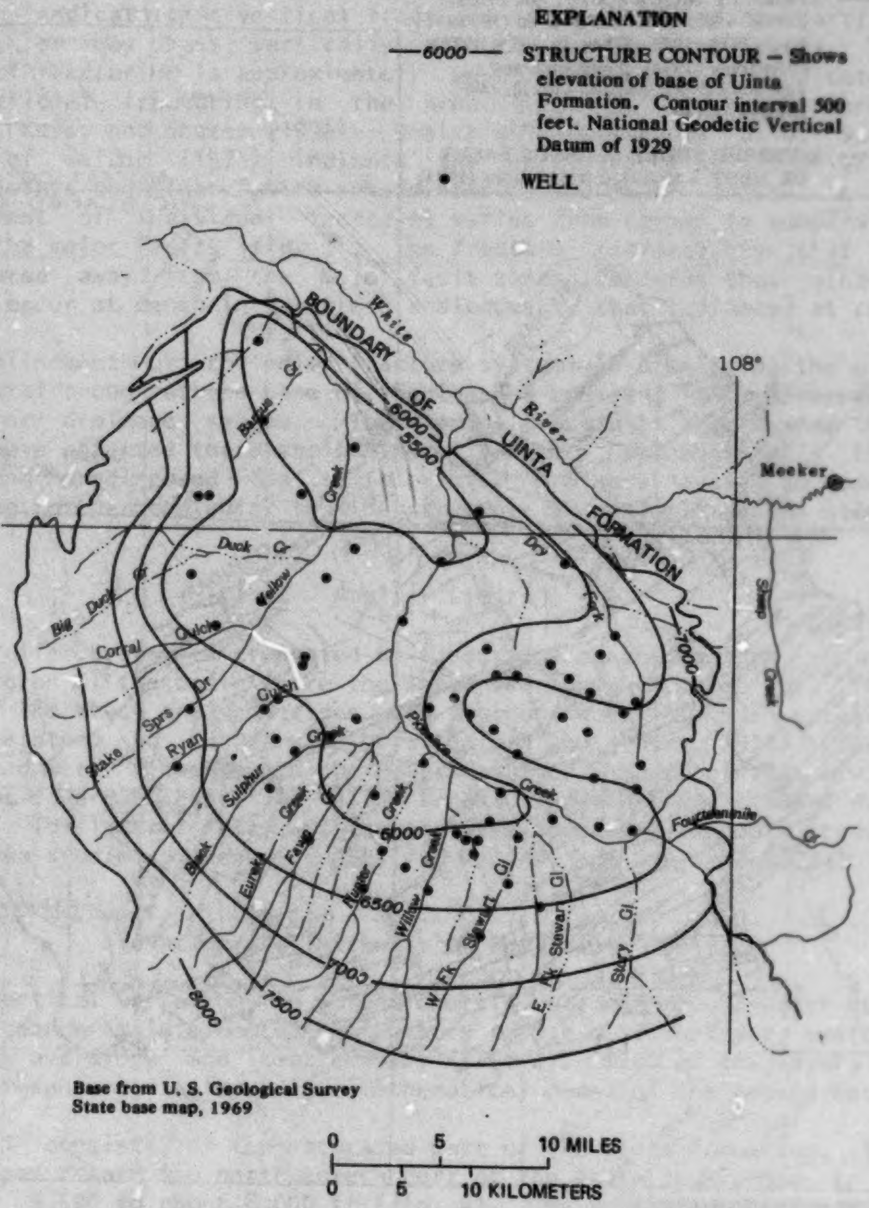
STRIKE OF MAJOR FAULT OR FAULT ZONE – Modified from Duncan (1976a-f), Hail (1970, 1973, 1974a, b, 1975, 1977), O'Sullivan (1974), Pipiringos and Johnson (1976), Roehler (1972), and Ziemba (1974)

INFERRED STRIKE OF MINOR FAULT OR JOINT – Modified from Welder (1971)

108°
40°
MOFFAT CO
RIO BLANCO CO
GARFIELD CO
DRAINAGE BASIN BOUNDARY
CATHEDRAL BLUFFS
GRAY HILLS
GRAND HOGBACK
ROAN PLATEAU
Price Creek
Wilson Creek
Good Spring Cr
Ninemile Gap
Coal Ridge
Colorow Mtn
Dick Ridge
Strawberry Cr
Sulphur Cr
Curtis Creek
Meeker
White River
Fletcher Gl
Spring Creek
West Fork
Ridge
Barcus Cr
Creek
Yellow Cr
Piceance Creek
Ryan Gulch
Black Sulphur Creek
Fawn Cr
Eureka Cr
Hunter Cr
Willow Creek
Stewart Gl
Fourteenmile Cr
Sheep Creek
Flag Creek
W Miller Cr
Rio Blanco
Horse Mtn
W Rifle Cr
Rifle Gap Res
Government Creek
Cathedral Creek
Lake Creek
Carr Cr
Brush Cr
Skinner Ridge
Clear Cr
West Fork
East Fork
1N
2
3
4
5
15
93
94
95
96
97
98
99
100
0
5
10
15 MILES
0
5
10
15 KILOMETERS

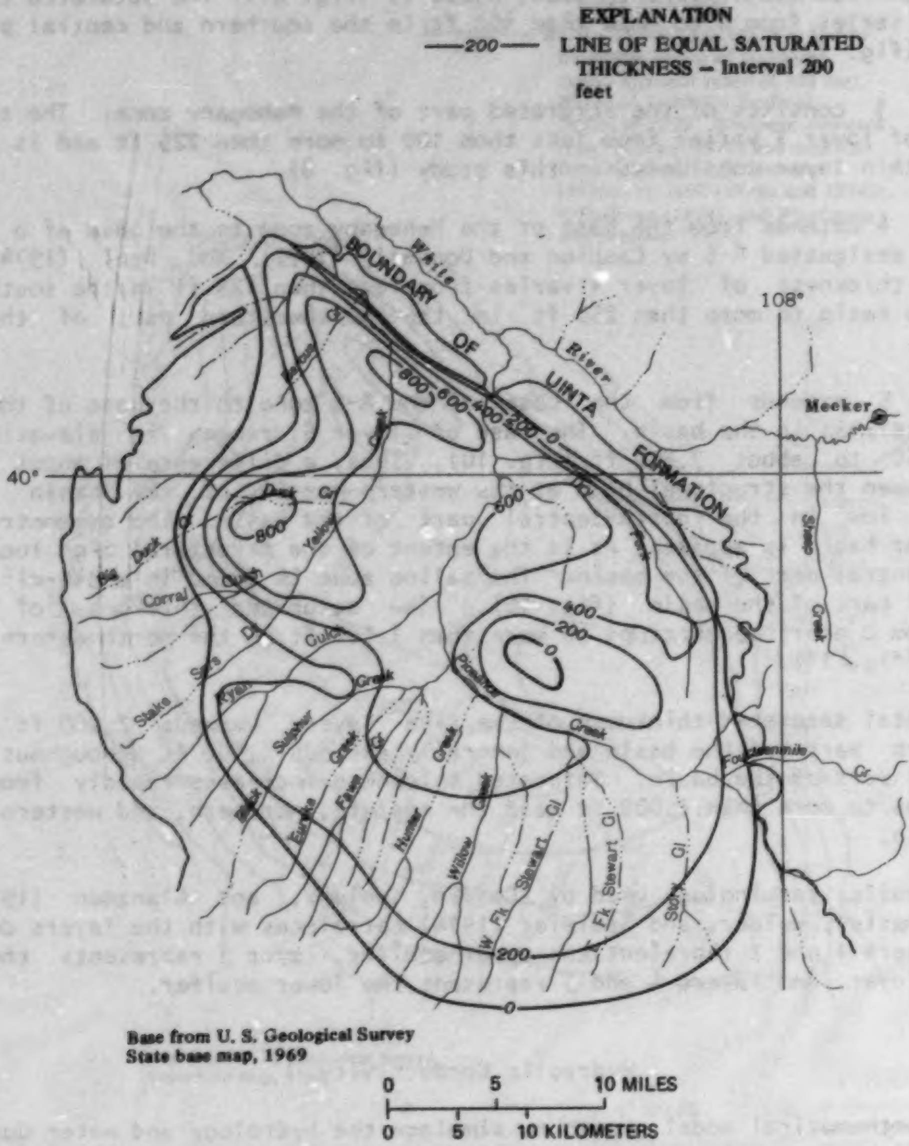
Base from U. S. Geological Survey
State base map, 1969

Figure 3.—Extent of surficial fracturing.


EXPLANATION
6000 STRUCTURE CONTOUR — Shows elevation of base of Uinta Formation. Contour interval 500 feet. National Geodetic Vertical Datum of 1929
● WELL
White River
BOUNDARY OF UINTA FORMATION
108°
Meeker
40°
Barcus Cr
Yellow Creek
Duck Cr
Big Duck Cr
Corral Gulch
Dry Fork
Piceance Creek
Stake Sprs Cr
Ryan Gulch
Sulphur Creek
Black
Eureka
Fawn
Hunter Creek
Willow Creek
Stewart Gl
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Sheep Creek
Fourteenmile Cr
5500
6000
6500
7000
7500
8000
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

Figure 4.--Structure contours on the base of the Uinta Formation.


EXPLANATION
—200— LINE OF EQUAL SATURATED THICKNESS – Interval 200 feet
BOUNDARY OF UINTA FORMATION
White River
108°
40°
Meeker
800
600
400
200
0
Big Duck
Corral
Gulch
Stake Springs
Ryan
Sulphur
Creek
Black
Eureka
Fawn
Hunter
Willow
W. Fk. Stewart Gl.
Fk. Stewart Gl.
Story Gl.
Piceance
Yellow
Fourteenmile
Stake Creek
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 5.—Saturated thickness of the Uinta Formation.

Layer 2 consists of the saturated part of the Parachute Creek Member above the Mahogany zone. The base of layer 2 (top of the Mahogany zone) slopes toward two structural lows in the northwestern and central parts of the basin and ranges in elevation from about 5,000 to about 8,000 ft (fig. 6). The saturated thickness of layer 2 varies from 0 to more than 400 ft in the southern and central parts of the basin (fig. 7).

Layer 3 consists of the saturated part of the Mahogany zone. The saturated thickness of layer 3 varies from less than 100 to more than 225 ft and is the most uniformly thin layer considered in this study (fig. 8).

Layer 4 extends from the base of the Mahogany zone to the base of a rich oil shale unit designated R-6 by Cashion and Donnell (1972) and Dyni (1974). The saturated thickness of layer 4 varies from less than 125 ft in the southwestern part of the basin to more than 250 ft in the northwestern part of the basin (fig. 9).

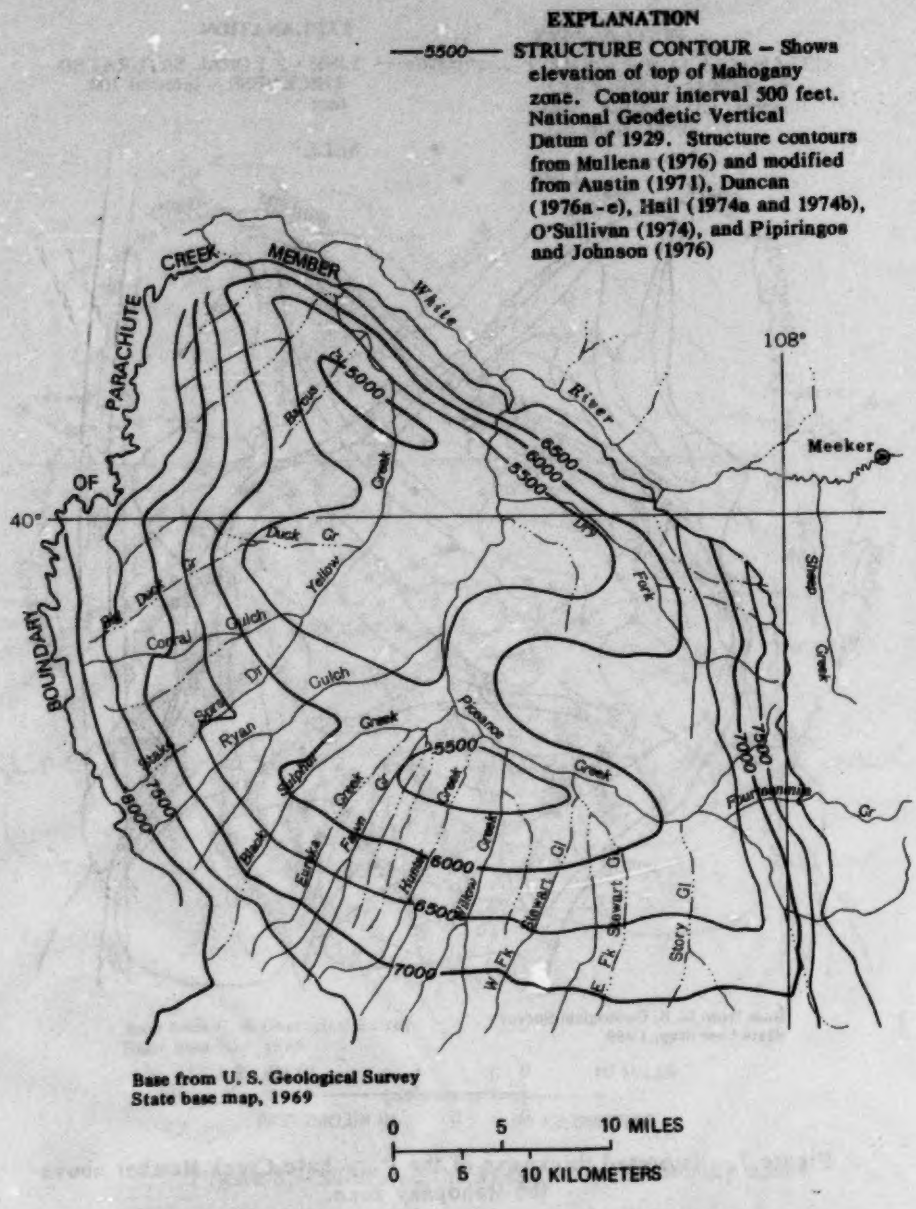
Layer 5 extends from the base of the R-6 zone to the base of the water-bearing materials in the basin. The base of layer 5 ranges in elevation from about 4,250 to about 7,500 ft (fig. 10). Thus, a difference of about 3,250 ft exists between the structural high at the western margin of the basin and the structural low in the north-central part of the basin. The asymmetry of the ground-water basin is apparent as is the extent of the structural high located in the east-central part of the basin. The saline zone is found in a 340-mi^2 area in the central part of the basin (fig. 10). The saturated thickness of layer 5 varies from 0 near the outcrops to more than 1,000 ft in the northeastern part of the basin (fig. 11).

The total saturated thickness of the five layers exceeds 2,000 ft in the northeastern part of the basin and generally exceeds 1,500 ft throughout most of the central part of the basin. Saturated thickness increases rapidly from 0 at the outcrops to more than 1,000 ft near the eastern, northern, and western margins of the basin.

The aquifer terminology used by Coffin, Welder, and Glanzman (1971) and Weeks, Leavesley, Welder, and Saulnier (1974) correlates with the layers described above. Layers 1 and 2 represent the upper aquifer, layer 3 represents the leaky confining layer, and layers 4 and 5 represent the lower aquifer.

Hydraulic Conductivity

The mathematical model chosen to simulate the hydrology and water quality in the Piceance basin required a more detailed areal and vertical distribution of hydraulic conductivity than had been presented in reports of earlier studies. New estimates of lateral and vertical hydraulic conductivity were made using data presented by Ficke, Weeks, and Welder (1974), Weeks and Welder (1974), Weeks, Leavesley, Welder, and Saulnier (1974), Wright Water Engineers, Inc. (1975), Ashland Oil, Inc. and Shell Oil Co., Operator (1976), Campbell (1977), and Dale

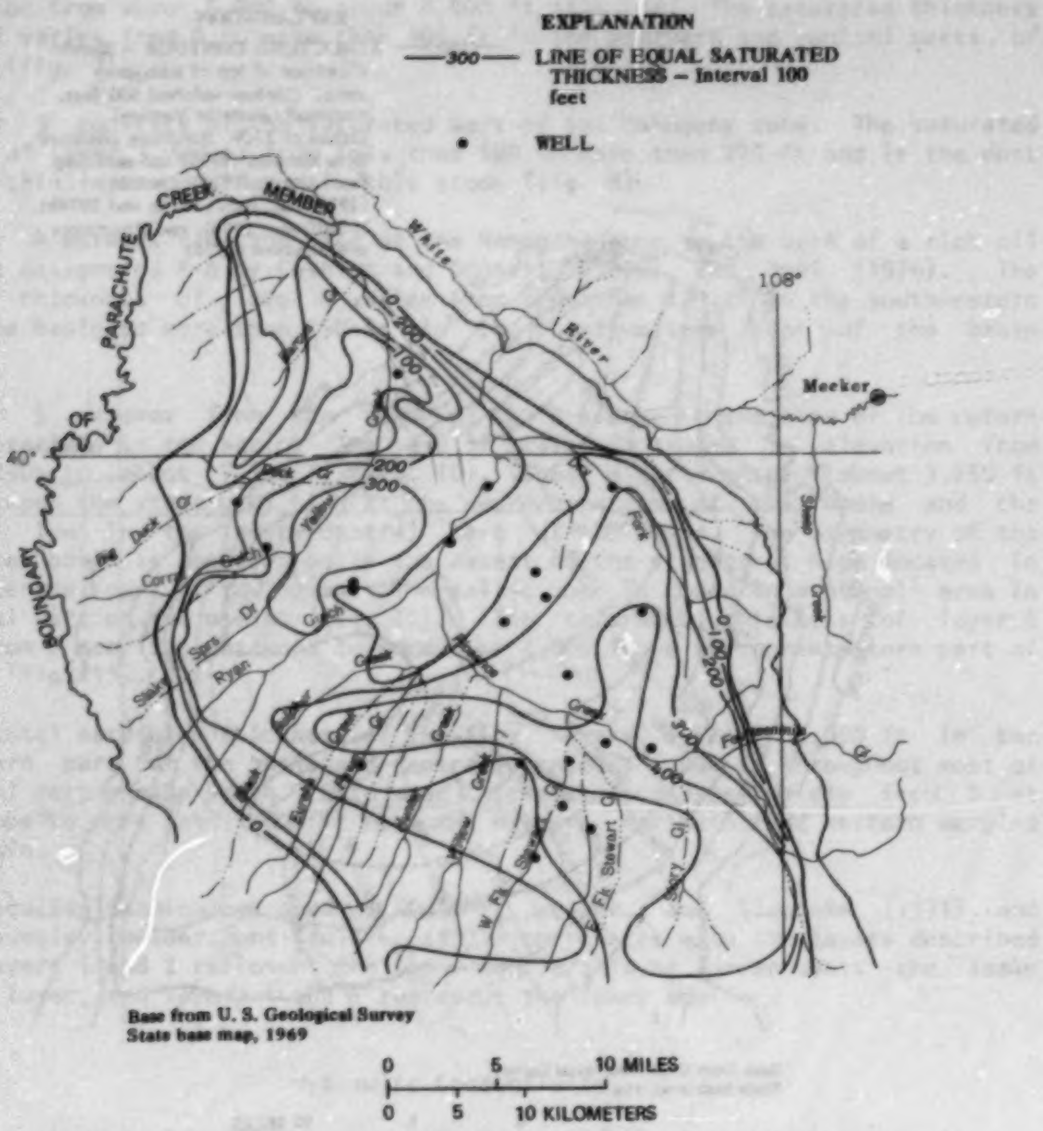

PARACHUTE CREEK MEMBER
BOUNDARY OF
White River
108°
Meeker
40°
Barcus Gr
Greek
Duck Gr
Big Duck Cr
Yellow
Corral Gulch
Dry Gulch
Spring
Ryan
Greek
Piceance
Greek
Dry Fork
Sheep Greek
Fourmile Gr
Black
Sulphur
Eureka
Greek
Fawn Gl
Greek
Hunter
Greek
Willow
Stewart Gl
W Fk
Stewart Gl
E Fk Stewart
Story Gl
Stake
5000
5500
6000
6500
7000
7500
8000
0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

—5500— **STRUCTURE CONTOUR – Shows elevation of top of Mahogany zone. Contour interval 500 feet. National Geodetic Vertical Datum of 1929. Structure contours from Mullens (1976) and modified from Austin (1971), Duncan (1976a-e), Hail (1974a and 1974b), O'Sullivan (1974), and Pipiringos and Johnson (1976)**

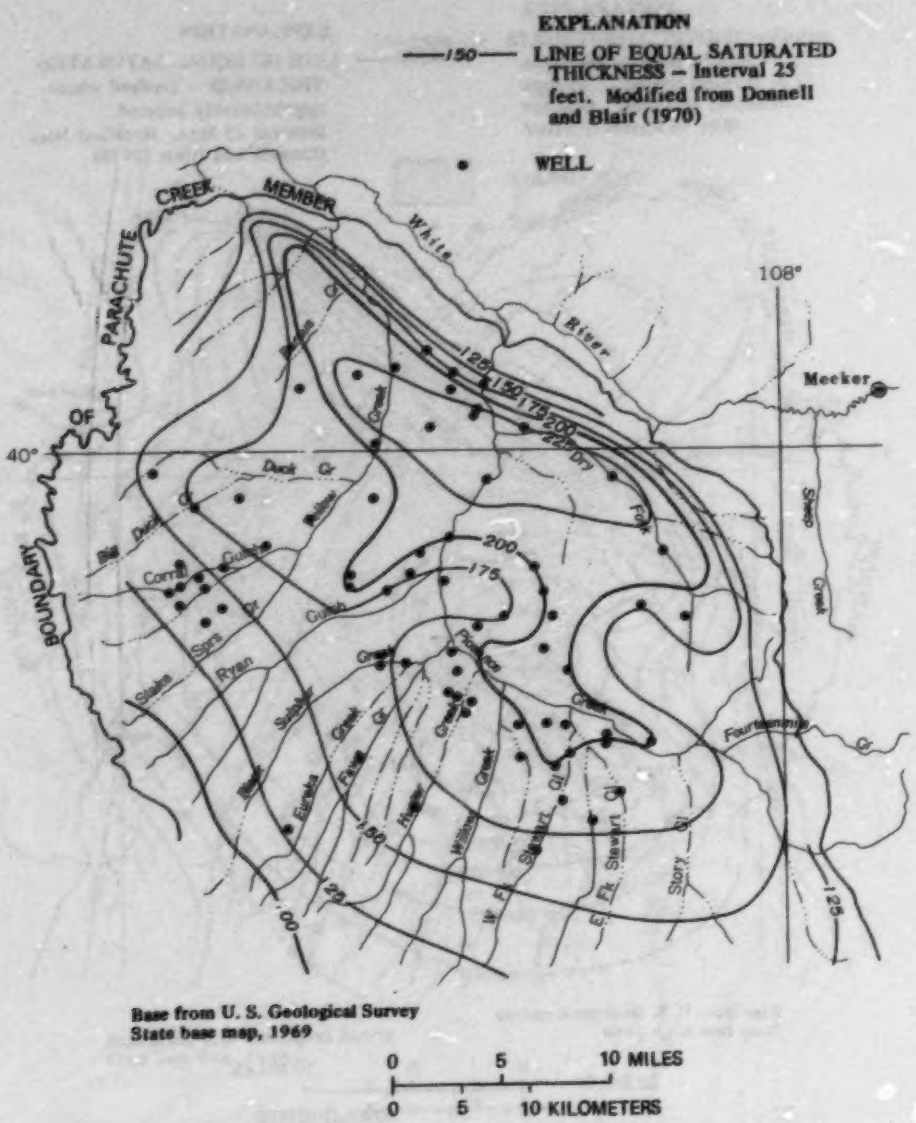
Base from U. S. Geological Survey State base map, 1969

Figure 6.–Structure contours on the top of the Mahogany zone.


EXPLANATION
300 LINE OF EQUAL SATURATED THICKNESS – Interval 100 feet
WELL
BOUNDARY OF PARACHUTE CREEK MEMBER
White River
Meeker
108°
40°
Piceance Cr
Yellow Cr
Duck Cr
Big Duck Cr
Corral Gulch
Ryan Gulch
Stake Spgs Dr
Black Sulphur Cr
Hunter Cr
Fawn Cr
Stewart Gulch
W Fk Stewart Gulch
E Fk Stewart Gulch
Sorghum Gulch
Parachute Creek
Fork
Stake Creek
Big Jimmy Gulch
0
100
200
300
400
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

Figure 7.--Saturated thickness of the Parachute Creek Member above the Mahogany zone.


EXPLANATION
150
LINE OF EQUAL SATURATED THICKNESS – Interval 25 feet. Modified from Donnell and Blair (1970)
● WELL
BOUNDARY OF PARACHUTE CREEK MEMBER
White River
Meeker
108°
40°
125
150
175
200
225
Dry Fork
Sheep Creek
Fourteenmile Gr
Duck Gr
Big Duck Cr
Corral Gulch
Sprs Gr
Ryan
Stake
Sulphur
Greek
Eureka
Fawn Cr
Hogan
Willow
Piceance Creek
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Story Gl
Yellow Creek
Black Sulphur Creek
Gulch
0
5
10 MILES
0
5
10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 8.–Saturated thickness of the Mahogany zone.

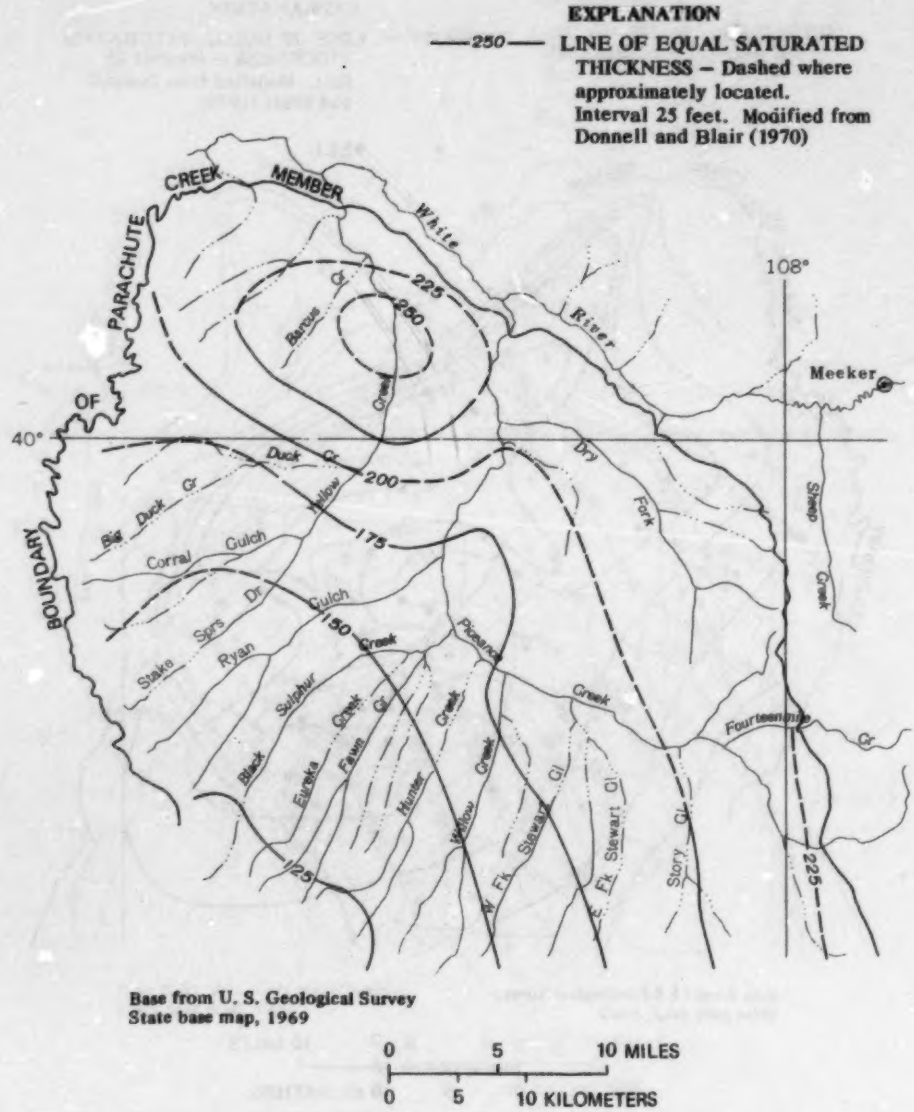

EXPLANATION
250
LINE OF EQUAL SATURATED THICKNESS - Dashed where approximately located. Interval 25 feet. Modified from Donnell and Blair (1970)
PARACHUTE CREEK MEMBER
BOUNDARY OF
White River
108°
40°
Meeker
225
250
200
175
150
125
225
Barcus Cr
Creek
Duck Cr
Big Duck Gr
Yellow
Corral Gulch
Dry Fork
Sheep Creek
Sprs Dr Gulch
Stake Ryan Creek
Piceance Creek
Sulphur
Black
Eureka Creek
Fawn Cr
Hunter
Creek
Willow
Greek
W. Fk
Stewart Gl
Stewart Gl
E. Fk
Story Gl
Fourteenmile Cr
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 9.--Saturated thickness of the interval from the base of the Mahogany zone to the base of the R-6 zone.

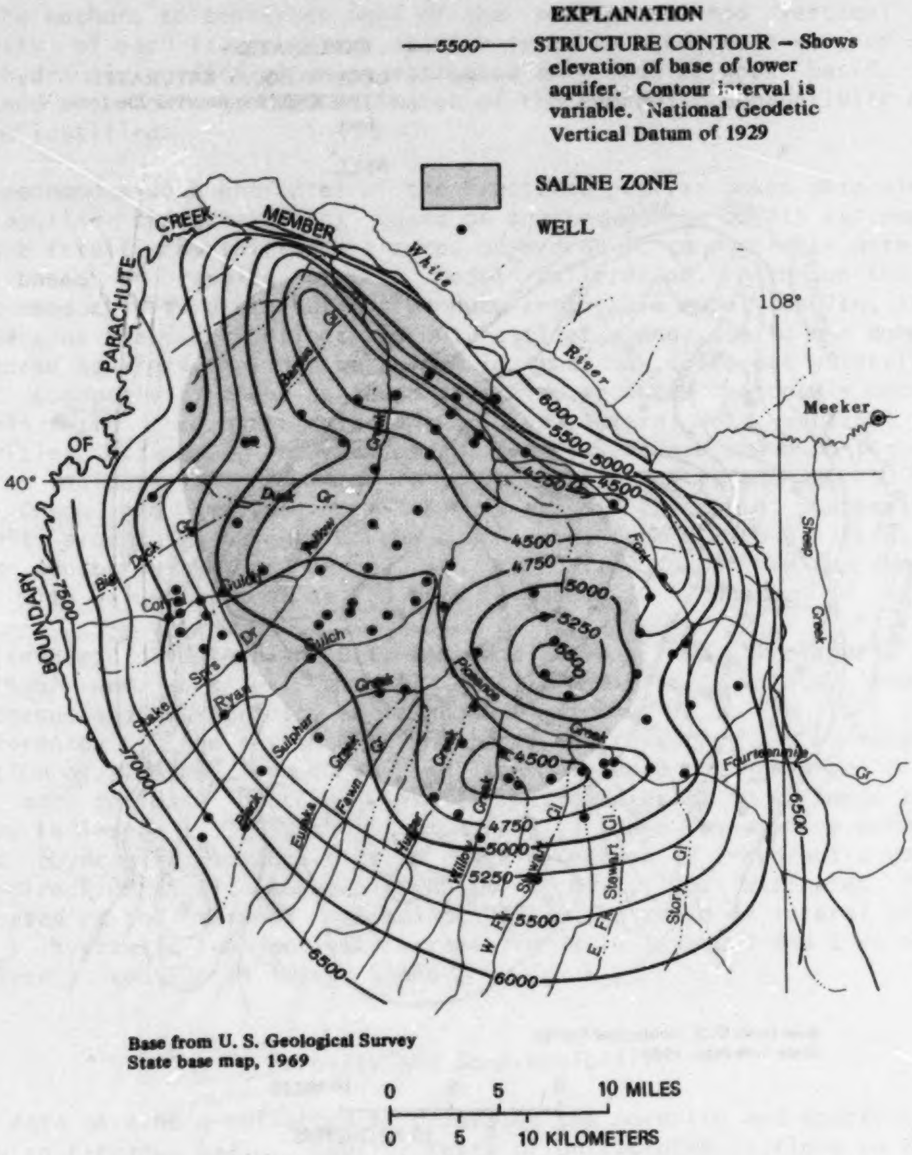
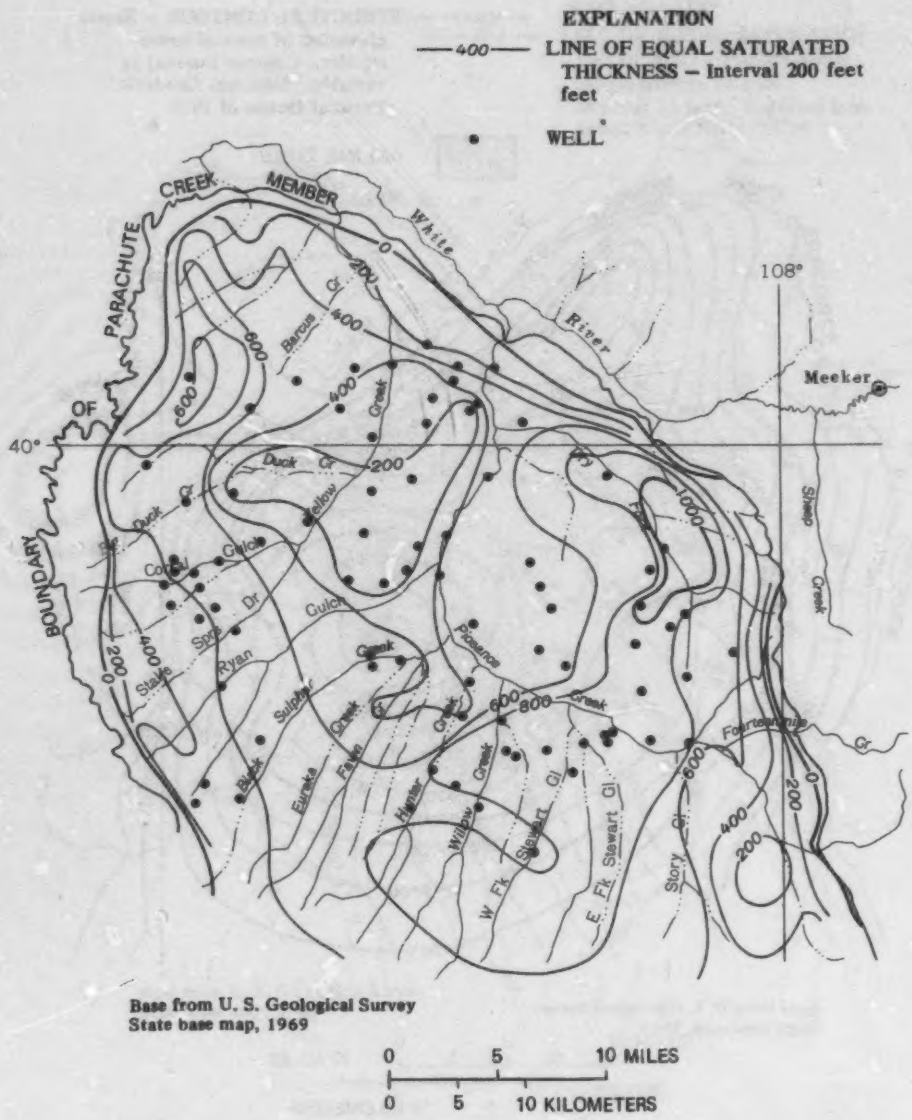

EXPLANATION
5500
STRUCTURE CONTOUR – Shows elevation of base of lower aquifer. Contour interval is variable. National Geodetic Vertical Datum of 1929
SALINE ZONE
WELL
PARACHUTE CREEK MEMBER
BOUNDARY OF
White River
108°
40°
Meeker
6000
5500
5000
4500
4250
4750
5250
6500
7000
7500
Piceance Creek
Yellow Creek
Fourteenmile Gr
Sheep Creek
Fork
Duck Gr
Big Duck Gr
Corral Gulch
Ryan Gulch
Spring Dr
Stake Spring
Black Sulphur Creek
Eureka Gr
Fawn Creek
Hatch Gulch
Willow Creek
W. Fk Stewart Gl
E. Fk Stewart Gl
Story Gl
Barcus Gr
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 10.--Structure contours on the base of the lower aquifer.


EXPLANATION
400 LINE OF EQUAL SATURATED THICKNESS – Interval 200 feet feet
● WELL
PARACHUTE CREEK MEMBER
BOUNDARY OF
White River
108°
40°
Meeker
Barcus Cr
Creek
Duck Cr
Yellow
Corral Gulch
Spring Dr
Gulch
Ryan
Stake
Sulphur
Black
Eureka
Greek
Fawn
Hunter
Willow
Piceance
Creek
W. Fk.
Stewart
Gl
E. Fk. Stewart Gl
Story Gl
Fourteenmile
Sheep Creek
Gr
0
200
400
600
800
1000

Base from U. S. Geological Survey
State base map, 1969

0 5 10 MILES
0 5 10 KILOMETERS

Figure 11.--Saturated thickness of the Parachute Creek Member below the base of the R-6 zone.

and Weeks (1978), as well as unpublished data on aquifer tests performed by F. A. Welder, J. B. Weeks, and G. J. Saulnier, Jr. Data from these sources and other information on the structure, stratigraphy, and faulting in the basin were used by the authors to construct maps of the horizontal and vertical hydraulic conductivity of each layer. Where aquifer tests or other data were of sufficient density, hydraulic conductivity was estimated on a node by node basis. In less well-defined areas only general estimates of the hydraulic conductivity over large areas were justified.

The nonhomogeneous character of the fractured aquifer makes determination of average aquifer characteristics based on scattered data points extremely difficult. As a result, the initial estimates of hydraulic conductivity were modified somewhat based on results of the model calibration. Although the resulting hydraulic conductivity distributions produce reasonable model results, it must be emphasized that the distributions are only estimates and, due to the complexity of the fractured aquifers, may not be unique in that a different distribution of hydraulic conductivity might be found that also produces reasonable model results and agrees with the hydrologic data. The lateral and vertical hydraulic conductivities estimated for each of the five layers are shown on figures 12-17. The figures indicate lateral hydraulic conductivities of as much as 2.0 ft/d along Piceance Creek and in the north-central part of the basin. Lateral hydraulic conductivity around the margins of the basin range from 0.1 to 0.6 ft/d. Vertical hydraulic conductivities as small as 7×10^{-4} ft/d occur in the Mahogany zone (layer 3) with values as much as 1.0 ft/d in layers 2, 4, and 5.

Aquifer-test data (Ashland Oil, Inc. and Shell Oil Co., Operator, 1976, and Sokol, 1976) and work by Campbell (1977) indicate that the aquifers are nonhomogeneous and anisotropic, as is shown on figures 12 to 17. This is due to the differences in the response of the rocks to fracturing and is related to the distribution of rich and lean zones and the presence or absence of solution cavities and collapse breccia. Insufficient data exist to estimate the lateral anisotropy in layers 1, 3, 4, and 5; as a result, these layers were assumed to be isotropic [hydraulic conductivity in the x-direction (K_x)=hydraulic conductivity in the y-direction (K_y)]. A ratio of K_x to K_y of 1.1 was estimated for all of layer 2 based on the work of Campbell (1977). The ratio of lateral (K_x) to vertical (K_z) hydraulic conductivity varies from 2 in layers 1 and 2 to as much as 100 in layer 3, and 500 in layers 4 and 5.

Porosity and Compressibility

Few data have been collected to determine the porosity and compressibility of the rocks in Piceance basin. Aquifer tests of unfractured sections in the saline zone performed in 1973 (Wolff and others, 1974) and 1976 (Dale and Weeks, 1978) indicate that these sections are virtually impermeable and likely have little effective porosity. By contrast, relatively large porosities occur as a result of voids in collapse breccia and solution cavities.

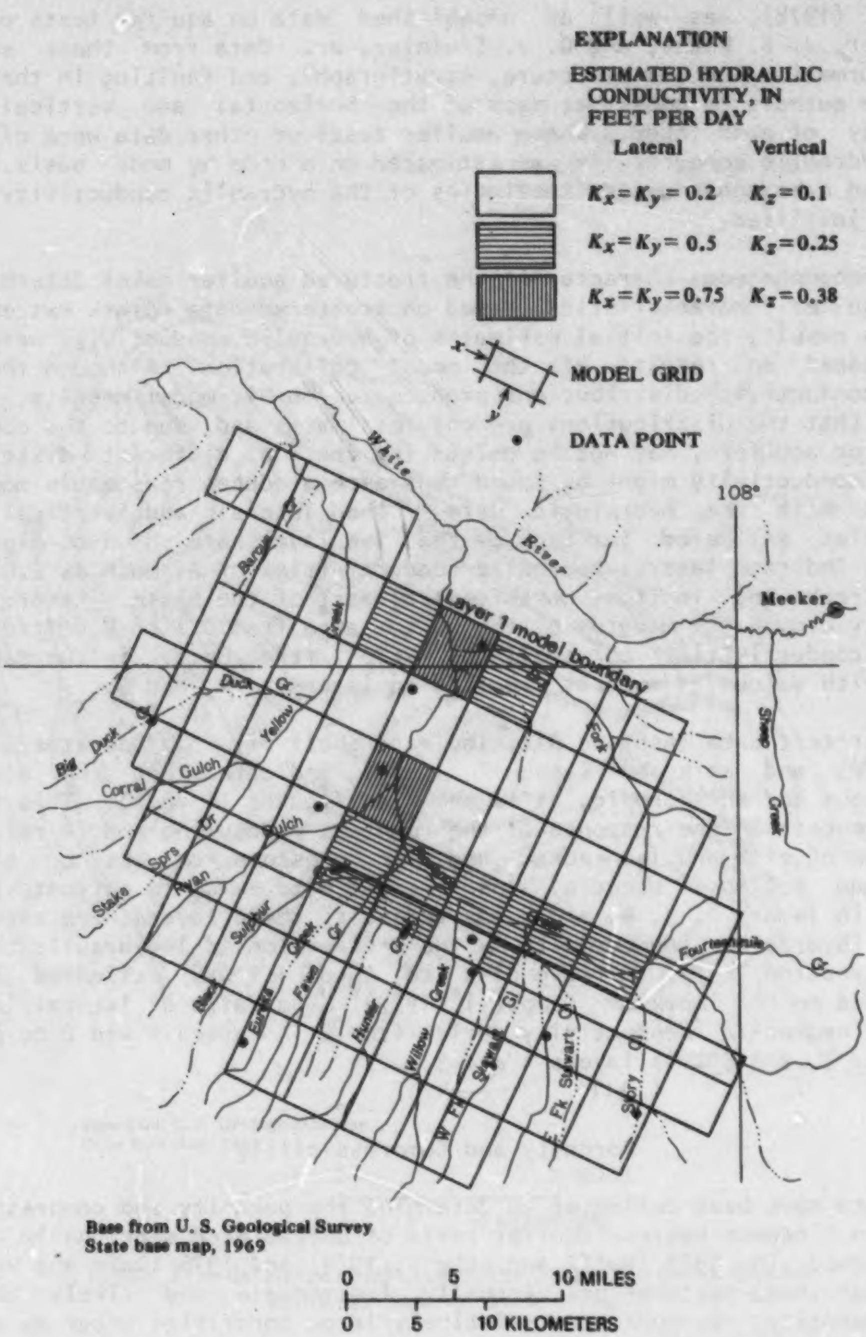
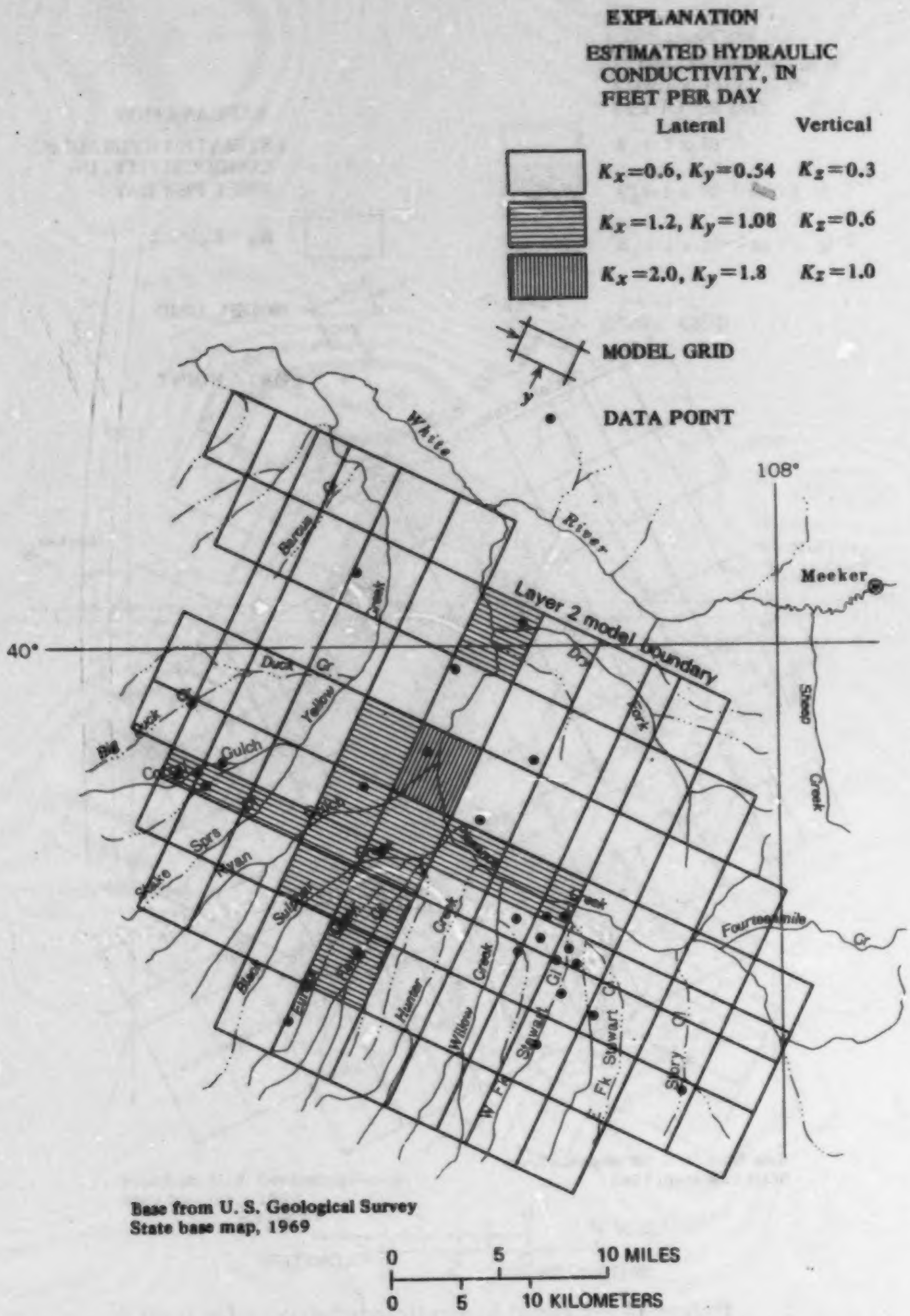

EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
Lateral
Vertical
$K_x = K_y = 0.2$
$K_z = 0.1$
$K_x = K_y = 0.5$
$K_z = 0.25$
$K_x = K_y = 0.75$
$K_z = 0.38$
x
y
MODEL GRID
DATA POINT
White
River
108°
Meeker
40°
Layer 1 model boundary
Barcus
Cr
Creek
Duck
Yellow
Big
Corral
Gulch
Spring
Stake
Ryan
Sulphur
Black
Eureka
Fawn
Hunter
Willow
Stewart
W. Fk.
E. Fk. Stewart
Story
Gulch
Cork
Sheep
Fourteenmile
Base from U. S. Geological Survey
State base map, 1969
0
5
10 MILES
0
5
10 KILOMETERS

Figure 12.—Lateral and vertical hydraulic conductivity for layer 1.


EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
Lateral
Vertical
K_x=0.6, K_y=0.54 K_z=0.3
K_x=1.2, K_y=1.08 K_z=0.6
K_x=2.0, K_y=1.8 K_z=1.0
x
y
MODEL GRID
DATA POINT
108°
40°
White
River
Meeker
Layer 2 model boundary
Barcus
Cr
Yellow
Creek
Duck Cr
Dry
Fork
Sheep
Creek
Big
Duck
Cr
Gulch
Corral
Spring
Spgs
Ryan
Stake
Sulphur
Creek
Piceance
Black
Hunter
Creek
Willow
Creek
W Fk
Stewart
Gl
E Fk
Stewart
Cr
Story
Gl
Fourteenmile
Gr
0
5
10 MILES
0
5
10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 13.--Lateral and vertical hydraulic conductivity for layer 2.

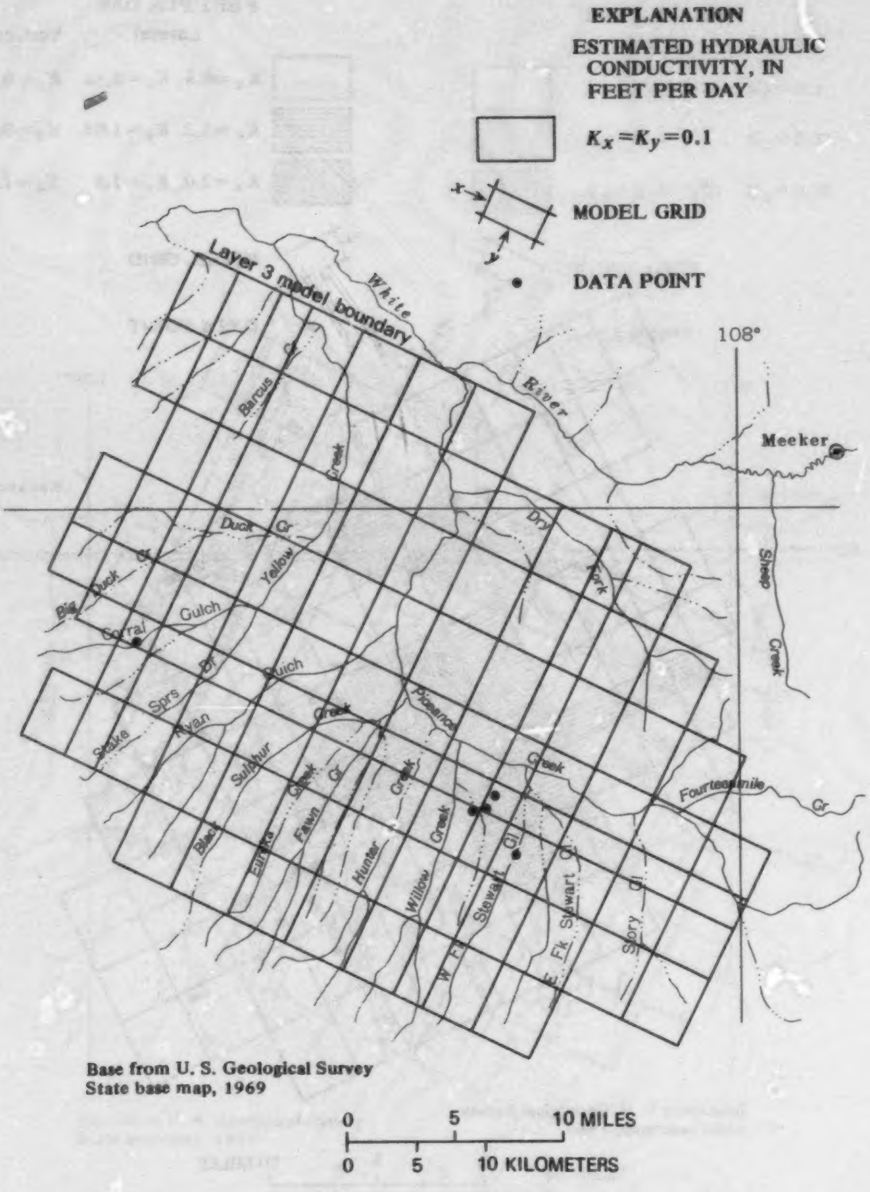
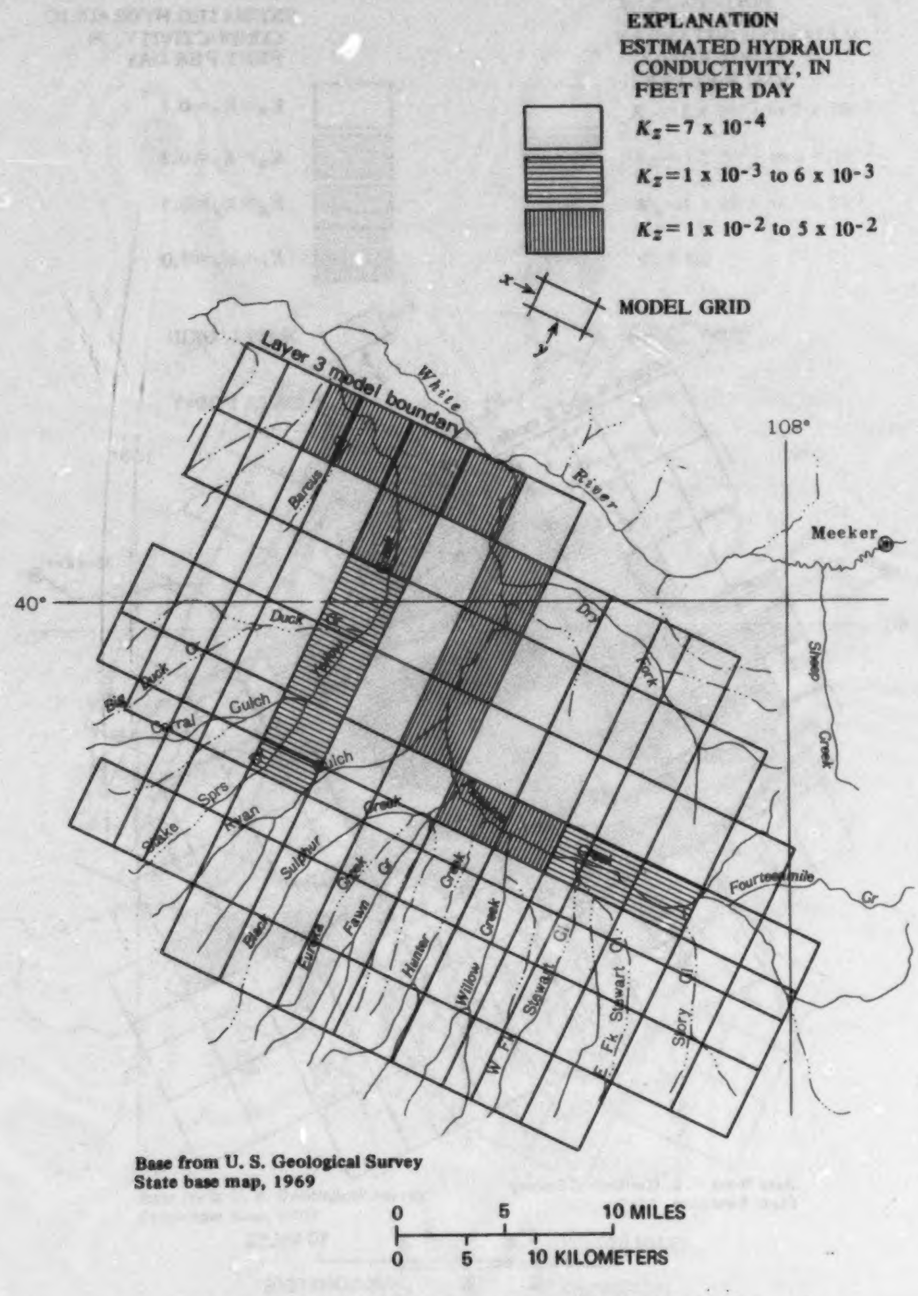
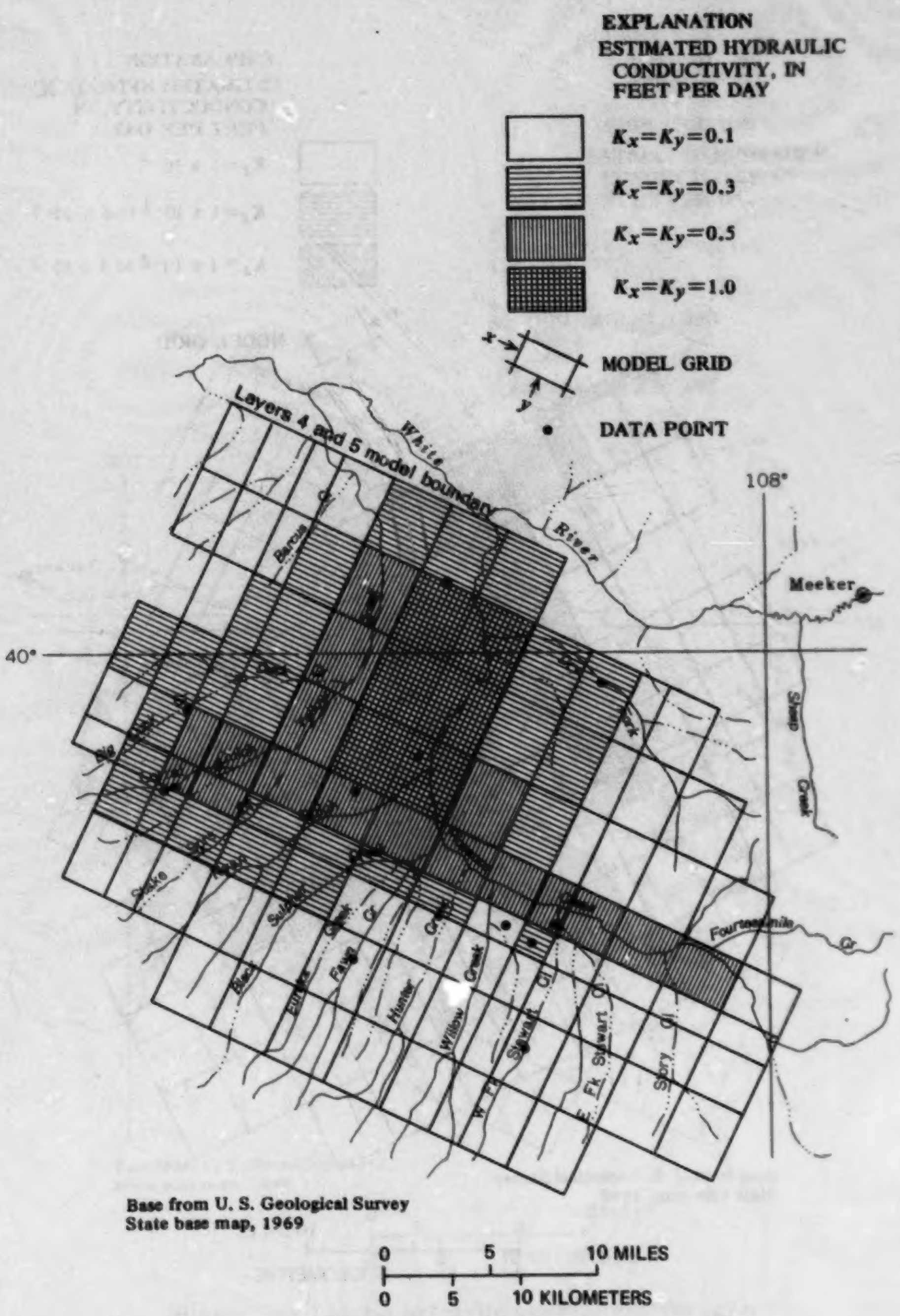

EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
$K_x = K_y = 0.1$
MODEL GRID
x
y
DATA POINT
Layer 3 model boundary
White River
108°
Meeker
40°
Barcus Gl
Creek
Duck Gr
Yellow
Big Duck Gl
Corral Gulch
Gulch
Dry Fork
Sheep Creek
Snake Sprs Dr
Ryan
Creek
Piceance
Creek
Fourteenmile Gr
Sulphur
Creek
Black
Eureka
Creek
Fawn Gl
Hunter
Creek
Willow
Creek
W. Fk.
Stewart Gl
E. Fk. Stewart Gl
Story Gl
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 14.--Lateral hydraulic conductivity for layer 3.


EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
$K_z = 7 \times 10^{-4}$
$K_z = 1 \times 10^{-3}$ to 6×10^{-3}
$K_z = 1 \times 10^{-2}$ to 5×10^{-2}
x
y
MODEL GRID
Layer 3 model boundary
White River
108°
Meeker
40°
Barcus
Duck Cr
Big Duck Cr
Corral Gulch
Gulch
Dry Fork
Sheep Creek
Sprs
Ryan
Snake
Sulphur
Creek
Cr
Black
Eureka
Fawn
Hunter
Creek
Willow
Creek
W Fk Stewart Cr
E Fk Stewart Cr
Story Cr
Fourteenmile Cr
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

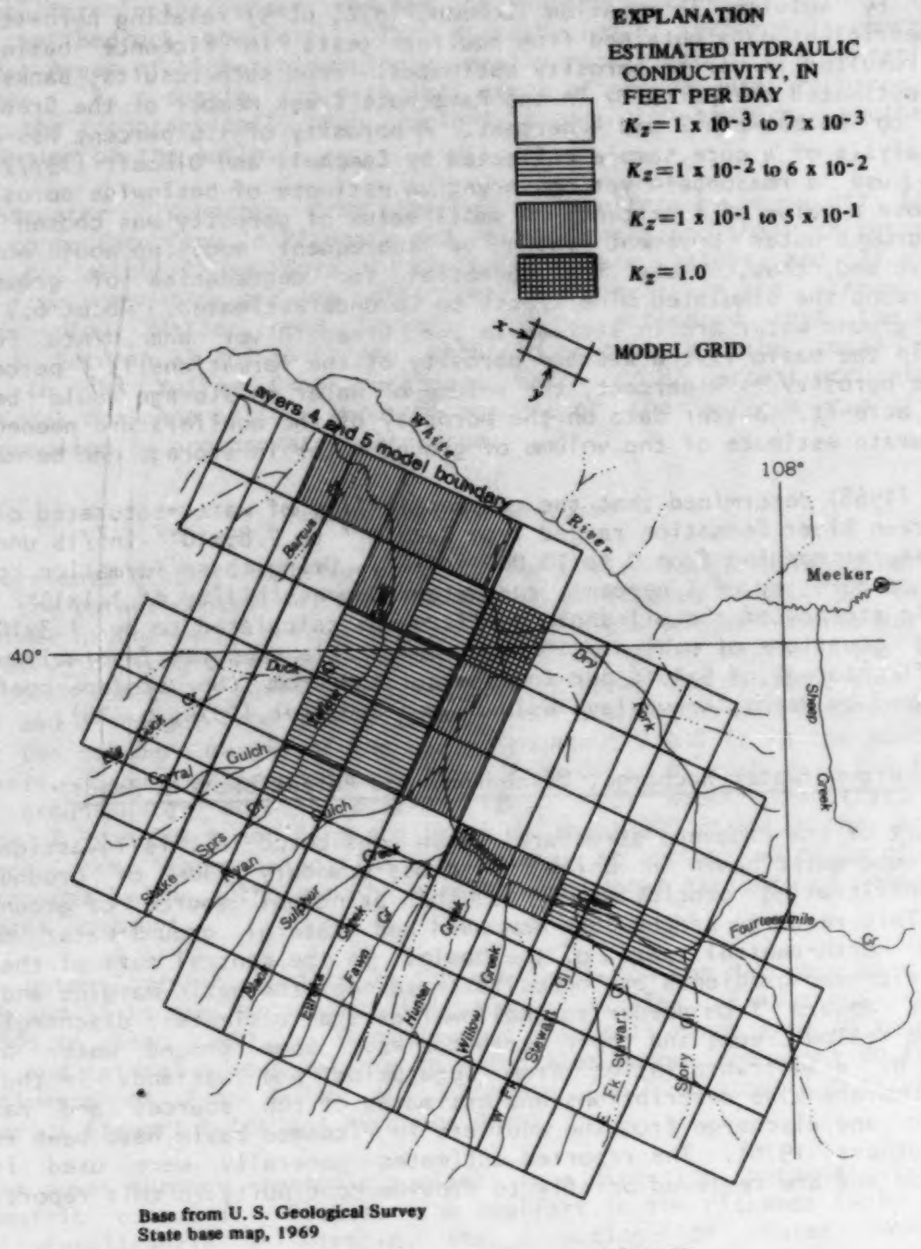
Figure 15.-- Vertical hydraulic conductivity for layer 3.



EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
$K_x=K_y=0.1$
$K_x=K_y=0.3$
$K_x=K_y=0.5$
$K_x=K_y=1.0$
x
y
MODEL GRID
DATA POINT
Layers 4 and 5 model boundary
White River
108°
40°
Meeker
Sheep Creek
Fourteenmile Cr
Barcus Cr
Big Duck Cr
Stake Springs Draw
Sulfur Creek
Black
Ellison
Fawn Cr
Hunter
Willow Creek
W. Fk. Stewart Cr
E. Fk. Stewart Cr
Spring Cr
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 16.-- Lateral hydraulic conductivity for layers 4 and 5.


EXPLANATION
ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
K_z=1 x 10^{-3} to 7 x 10^{-3}
K_z=1 x 10^{-2} to 6 x 10^{-2}
K_z=1 x 10^{-1} to 5 x 10^{-1}
K_z=1.0
x
y
MODEL GRID
Layers 4 and 5 model boundary
White River
108°
40°
Meeker
Sheep Creek
Dry Fork
Duck Cr
Yellow Cr
Barcus Cr
Black Cr
Corral Gulch
Box Elder Gulch
Snake Sprs Cr
Ryan Gulch
Sulphur Creek
Black Cr
Fawn Creek
Hunter Cr
Willow Creek
Stewart Gl
E Fk Stewart Gl
Story Gl
Fourteenmile Cr
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 17.--Vertical hydraulic conductivity for layers 4 and 5.

Porosity estimates by the authors and by Banks and Franciscotti (1976) have been made by solving an equation (Lohman, 1972, p. 9) relating porosity to the storage-coefficient data obtained from aquifer tests in Piceance basin. This technique resulted in varied porosity estimates. From such results, Banks and his coworkers estimated the porosity in the Parachute Creek Member of the Green River Formation to be between 2 and 4 percent. A porosity of 1.6 percent was obtained from an analysis of a core sample collected by Campbell and Olhoeft (1977). In an effort to use a reasonable yet conservative estimate of basinwide porosity, the authors chose a value of 1 percent. A small value of porosity was chosen so the rate of ground-water movement shown by subsequent modeling would not be too conservative and, thus, cause the potential for degradation of ground-water quality around the simulated mine tracts to be underestimated. About 6.7 million acre-ft of ground water are in storage in the Green River and Uinta Formation aquifers in the basin if the average porosity of the formations is 1 percent. If the average porosity is 4 percent, the volume of water in storage would be about 27 million acre-ft. Better data on the porosity of the aquifers are needed before a more accurate estimate of the volume of ground water in storage can be made.

Podio (1968) determined that the compressibility of water-saturated oil shale from the Green River Formation ranged from 2.6×10^{-7} to 2.85×10^{-7} in^2/lb under confining pressures ranging from 0 to 10,000 lb/in^2. Using these formation compressibilities, a porosity of 1 percent, and water compressibility of 3.1×10^{-6} in^2/lb, the specific storage of the oil-shale aquifers was calculated to be 1.3×10^{-7} per foot using equations of DeWiest (1969, p. 15). This compares favorably with the mean specific storage of 5×10^{-7} per foot calculated from the storage-coefficient data presented by Weeks, Leavesley, Welder, and Saulnier (1974, p. 28).

Ground-Water Recharge, Discharge, and Potentiometric Heads

The part of the Piceance structural basin considered in this investigation is a closed ground-water basin in which no cross-boundary flow of ground water occurs. Infiltrating precipitation is the principal source of ground-water recharge. This recharge causes both downward and lateral ground-water movement toward the north-central part of the basin. In the central part of the basin, potentiometric-head gradients are opposite those near the basin margins and ground water moves upward from deeper to shallower strata, ultimately discharging into Piceance and Yellow Creeks and their tributaries. Some ground water also is discharged by evapotranspiration from vegetation and wetlands in the stream valleys. Comprehensive descriptions and estimates of the sources and rates of recharge to and discharge from the aquifers in Piceance basin have been reported (Weeks and others, 1974). The reported estimates generally were used in this investigation and are reviewed briefly to provide continuity in this report.

Ground-Water Recharge and Discharge

Weeks, Leavesley, Welder, and Saulnier (1974) estimated that the principal source of ground-water recharge was snowpack melt water in areas with elevations greater than 7,000 ft. An estimated 33 to 36 ft^3/s of aggregate recharge occurs either as direct infiltration into the bedrock aquifers or by recharge to small alluvial aquifers in the upper reaches of numerous creeks, which, in turn, recharge the bedrock aquifers. The distribution of recharge is controlled by topography. Areas of higher elevation generally receive more precipitation than lower areas. As a result, the principal areas of ground-water recharge probably occur near the topographically high regions along the eastern, southern, and western margins of the basin.

Ground-water discharges from the bedrock aquifers by means of: (1) Direct discharge to surface flow in Piceance and Yellow Creeks and their tributaries; (2) discharge to alluvial aquifers in the major stream valleys; and (3) evapotranspiration from vegetation and wet soils located primarily in the stream valleys. Weeks, Leavesley, Welder, and Saulnier (1974) estimated that the aggregate discharge is between 33 and 36 ft^3/s, with 18 percent of the total discharge occurring in the Yellow Creek drainage basin and 82 percent occurring in the Piceance Creek drainage basin. About 80 percent of the surface runoff in the basin is supplied by ground-water discharge.

Potentiometric Surfaces

Measurements of the elevation of the static water level in wells were used to construct the potentiometric-surface maps shown on figures 18 and 19. Because of only minimal ground-water development as of 1977, the potentiometric surfaces are representative of long-term ground-water conditions in the basin. The elevation of the potentiometric surface in the aquifer above the Mahogany zone (fig. 18) (layers 1 and 2) ranges from about 5,800 ft near the mouths of Piceance and Yellow Creeks at the northern margin of the basin, to about 7,400 ft in the southern part of the basin. Ground-water gradients range from 20 to as much as 120 ft/mi and lateral ground-water pore velocities range from about 150 ft/yr near the confluence of Ryan Gulch and Piceance Creek to about 300 ft/yr in the area south of Piceance Creek. These velocities are based on an average porosity of 1 percent and are thought by the authors to be a reasonable upper estimate of the rate of ground-water movement.

The potentiometric surface in the aquifer below the Mahogany zone (fig. 19) (layers 4 and 5) is similar to that in the upper aquifer. Elevations range from about 5,800 to about 7,400 ft. Ground-water gradients range from 20 to as much as 130 ft/mi and lateral ground-water pore velocities range from about 90 ft/yr near the confluence of Ryan Gulch and Piceance Creek to about 140 ft/yr near the confluence of Stewart Gulch and Piceance Creek.

Water moves through isotropic aquifers in a direction perpendicular to the potentiometric contours. Because the aquifers in the Piceance basin apparently are not significantly anisotropic, the direction of water movement is approximately perpendicular to the contours. On the basis of the configurations of the potentiometric surfaces, water moves from recharge areas near the basin margins toward discharge areas along Piceance Creek and the lower reaches of Yellow Creek. The configuration of the potentiometric surfaces also indicates that water discharges along Dry Fork Creek and the downstream reaches of the creeks located between Black Sulphur and Willow Creeks.

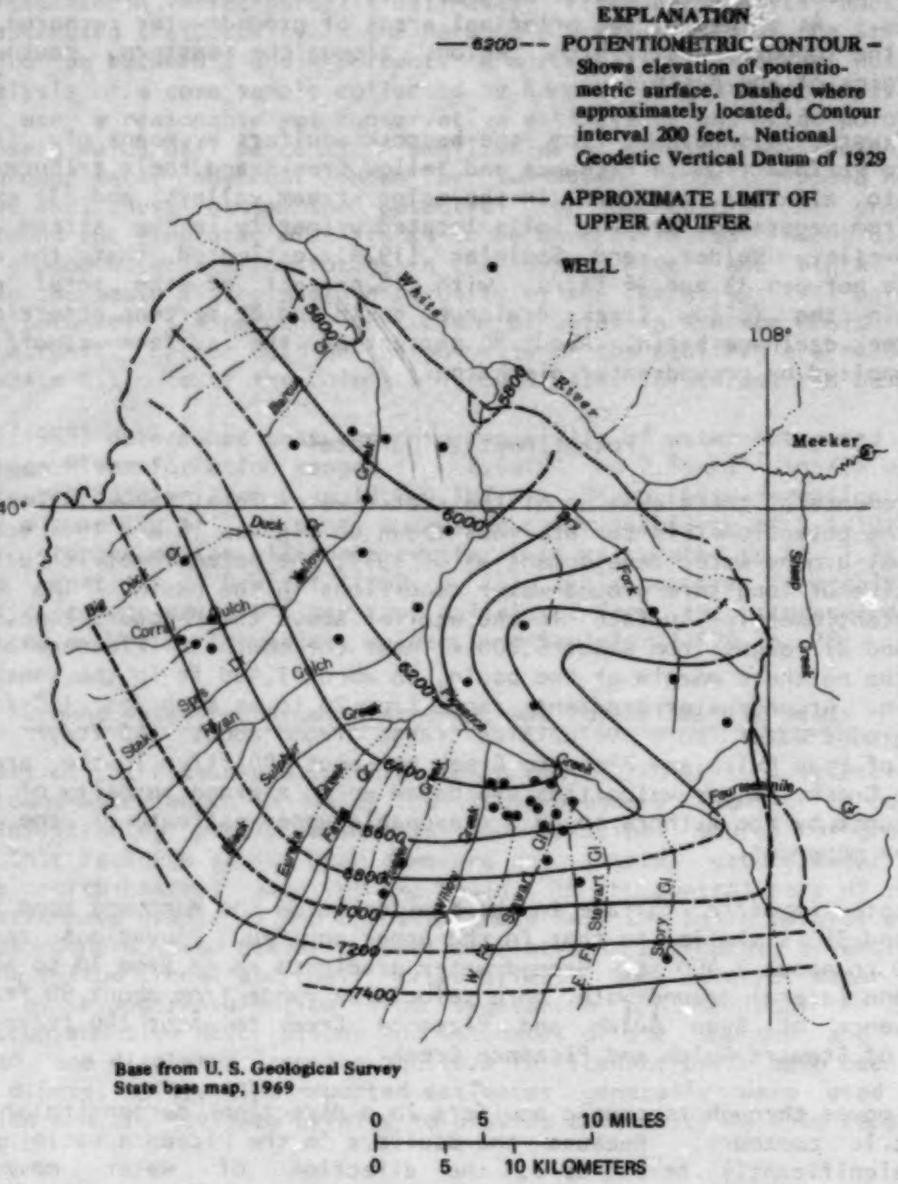

EXPLANATION
6200 POTENTIOMETRIC CONTOUR – Shows elevation of potentiometric surface. Dashed where approximately located. Contour interval 200 feet. National Geodetic Vertical Datum of 1929
APPROXIMATE LIMIT OF UPPER AQUIFER
WELL
108°
40°
Meeker
White River
Piceance Creek
Yellow Creek
Duck Cr
Big Duck Gl
Corral Gulch
Stake Springs Dr
Ryan Gulch
Sulphur
Black Sulphur Creek
Eureka
Fawn Cr
Hunter Cr
Willow Creek
Stewart Gl
E Fk Stewart Gl
W Fk
Story Gl
Fourteenmile Cr
Dry Fork
Sheep Creek
5600
5800
6000
6200
6400
6600
6800
7000
7200
7400
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 18.--Potentiometric surface of the upper aquifer.

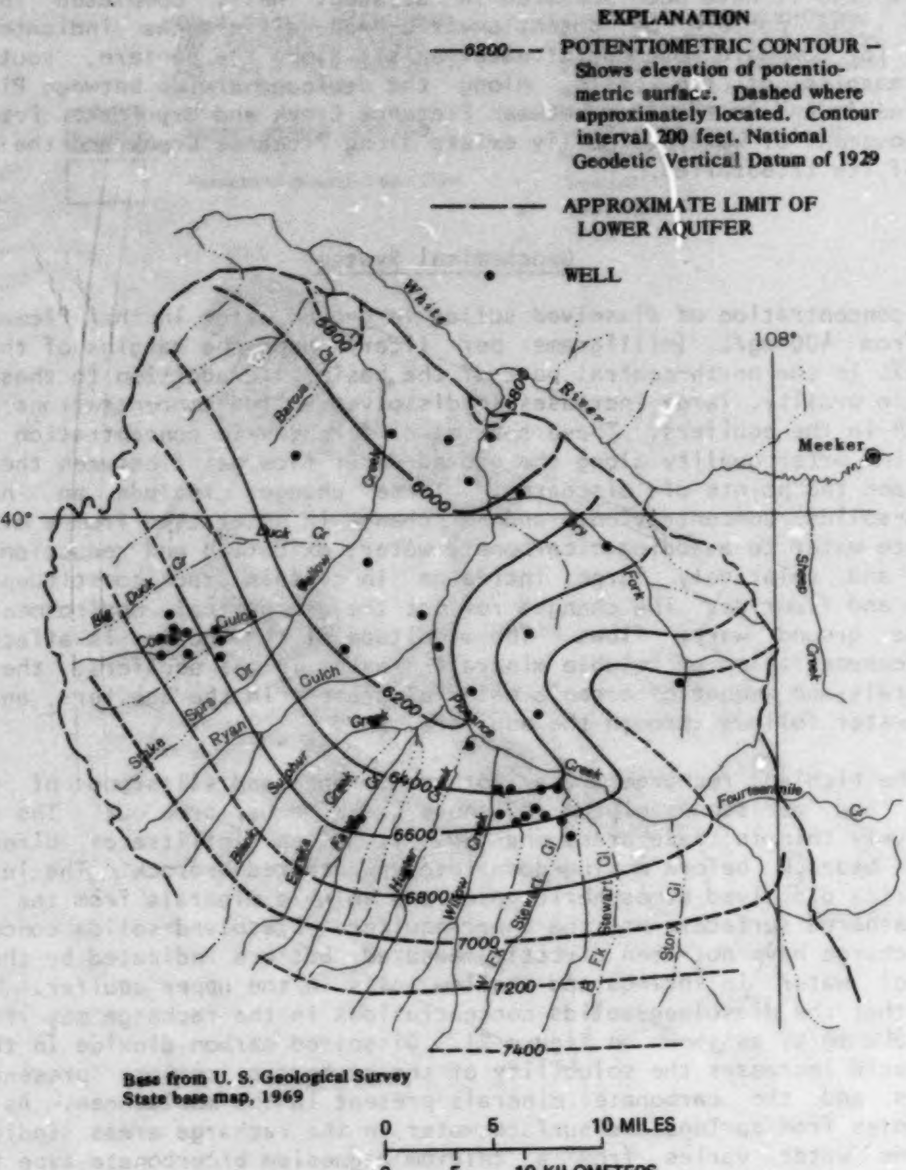

EXPLANATION
6200 POTENTIOMETRIC CONTOUR – Shows elevation of potentiometric surface. Dashed where approximately located. Contour interval 200 feet. National Geodetic Vertical Datum of 1929
APPROXIMATE LIMIT OF LOWER AQUIFER
WELL
108°
40°
Meeker
White River
Barcus Cr
Creek
Duck Cr
Big Duck Cr
Hollow
Corral
Gulch
Spring Dr
Gulch
Ryan
Stake
Sulphur
Creek
Black
Piceance
Creek
Fork
Sheep Creek
Fourteenmile Gl
Hunter
Willow
W Fk Stewart Gl
Fk Stewart Gl
Stewart Gl
Story Gl
5800
6000
6200
6400
6600
6800
7000
7200
7400
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

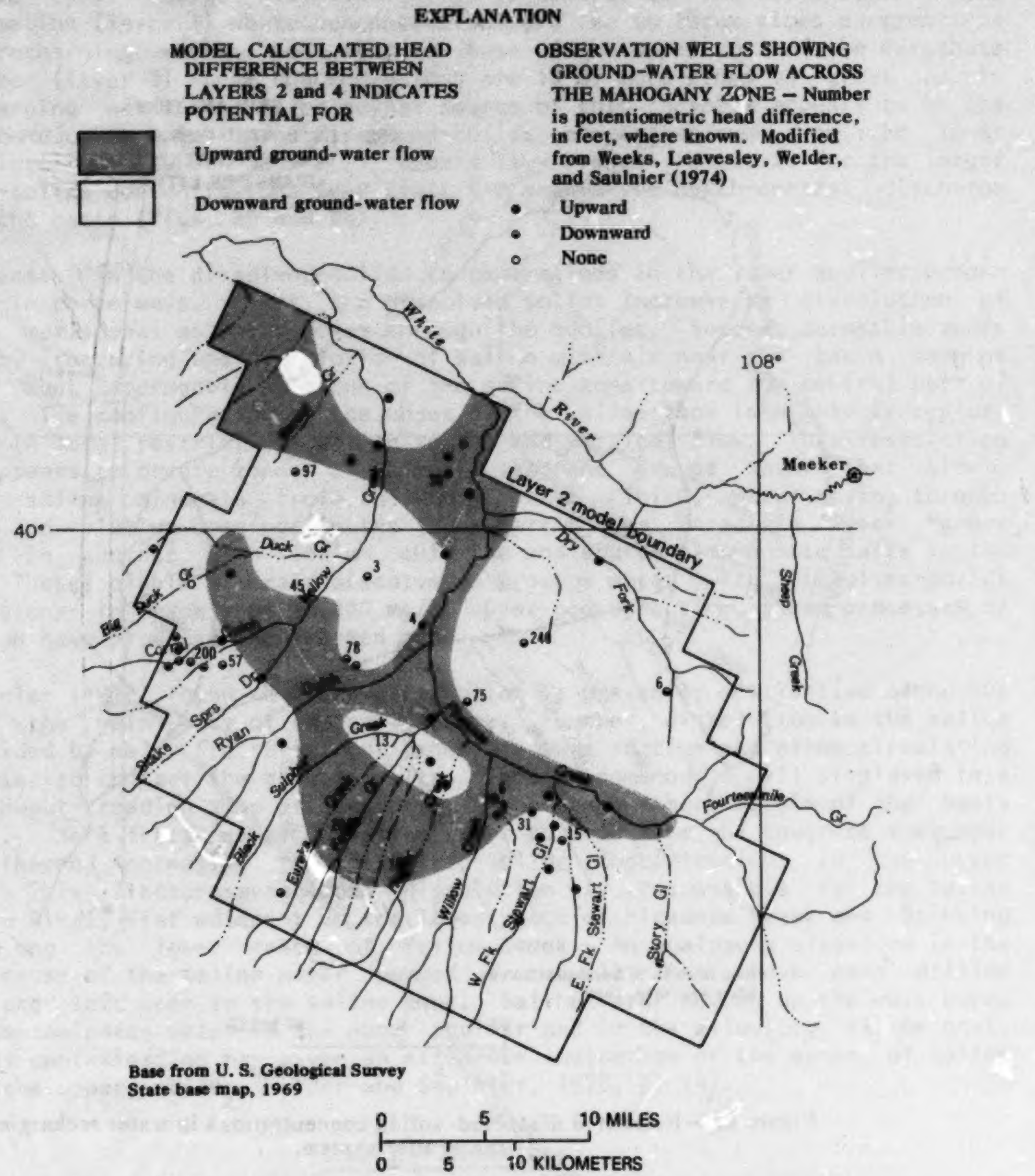
Figure 19.—Potentiometric surface of the lower aquifer.

The differences in the potentiometric heads in wells completed above and below the Mahogany zone are shown on figure 20. Potentiometric-head differences as large as 240 ft have been measured in adjacent wells completed in the two aquifers. The pattern of potentiometric-head differences indicates that the potential for downward movement of water exists along the eastern, southern, and western margins of the basin, along the drainage divide between Piceance and Yellow Creeks, and in the area between Piceance Creek and Dry Fork. Potential for upward movement of water primarily exists along Piceance Creek and the downstream reaches of its tributaries.

Geochemical System

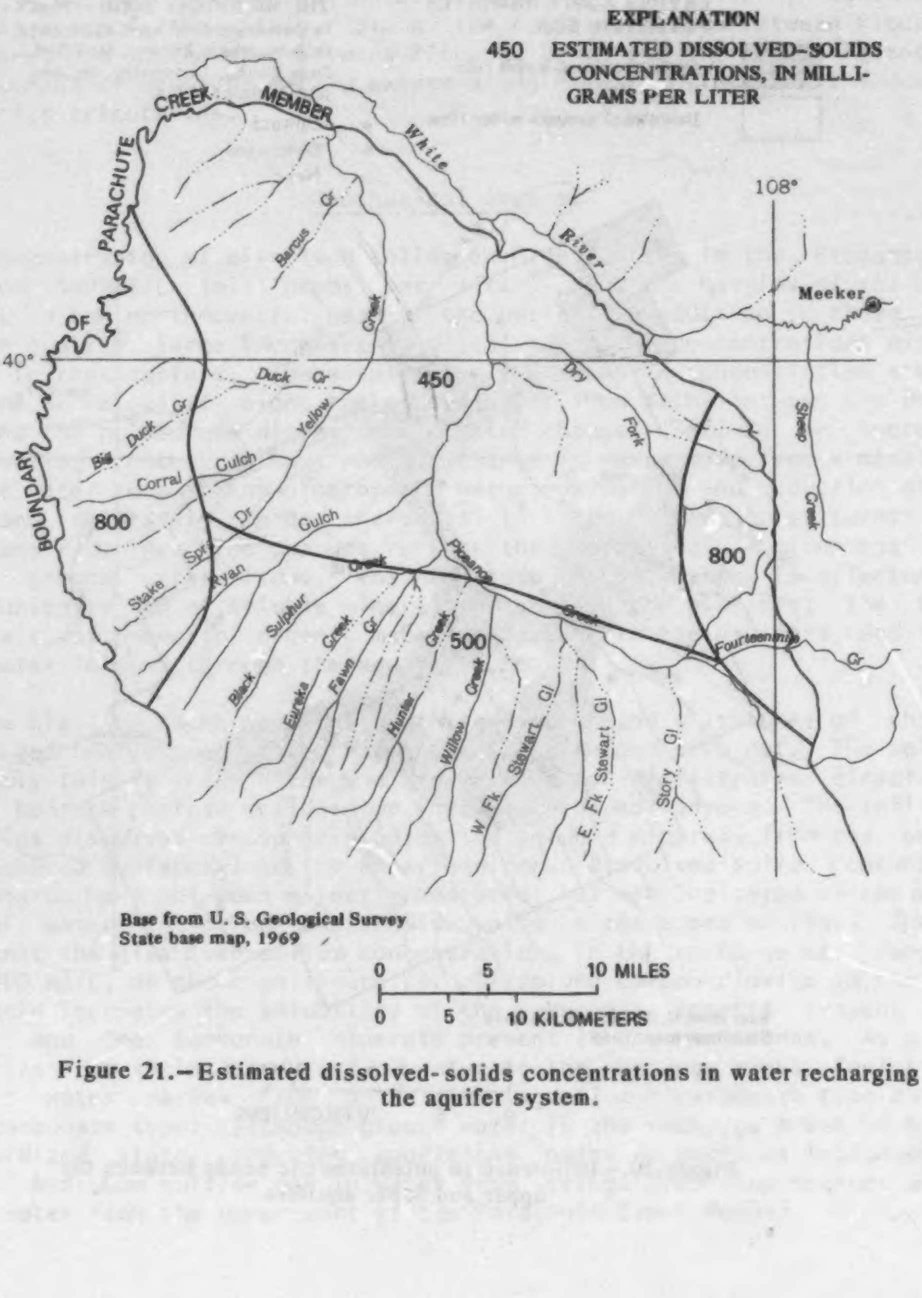
The concentration of dissolved solids in ground water in the Piceance basin ranges from 400 mg/L (milligrams per liter) near the margins of the basin to 40,000 mg/L in the north-central part of the basin. In addition to these lateral changes in quality, large increases in dissolved-solids concentrations also occur with depth in the aquifers. These spatial differences in concentration are due to changes in water quality along the ground-water flow paths between the points of recharge and the points of discharge. These changes include an increase in dissolved-solids concentration, and a change in water type from a mixed cation bicarbonate water to a sodium bicarbonate water, oxidation and reduction of sulfur species, and relatively large increases in certain trace constituents such as strontium and fluoride. The changes reflect the geochemical environment through which the ground water flows. The magnitude of the changes is affected by the type and concentration of soluble minerals present in the aquifers, the type of clay minerals and amount of organic material present in the aquifers, and the flow path the water follows through the aquifers.

In the highland recharge areas, both sandstones and siltstones of the Uinta Formation and marlstones of the Parachute Creek Member crop out. The soil cover is relatively thin in these areas and snowmelt often infiltrates directly into weathered bedrock before moving down into unweathered bedrock. The infiltrating water carries dissolved atmospheric gases and soluble minerals from the weathered and unweathered surfaces into the upper aquifer. Dissolved-solids concentrations in the recharge have not been directly measured, but are indicated by the chemical quality of water in springs and shallow wells in the upper aquifer. These data indicate that the dissolved-solids concentrations in the recharge may range from 450 to 800 mg/L, as shown on figure 21. Dissolved carbon dioxide in the form of carbonic acid increases the solubility of the carbonate cements present in the sandstones and the carbonate minerals present in the marlstones. As a result, water samples from springs and surface water in the recharge areas indicate that the ground water varies from a calcium magnesium bicarbonate type to a mixed cation bicarbonate type. Although ground water in the recharge areas is generally in an oxidized state, reducing conditions exist at depth as indicated by the presence of hydrogen sulfide gas in water from springs from deep sources and wells producing water from the upper part of the Parachute Creek Member.


EXPLANATION
MODEL CALCULATED HEAD DIFFERENCE BETWEEN LAYERS 2 and 4 INDICATES POTENTIAL FOR
▨ Upward ground-water flow
☐ Downward ground-water flow
OBSERVATION WELLS SHOWING GROUND-WATER FLOW ACROSS THE MAHOGANY ZONE — Number is potentiometric head difference, in feet, where known. Modified from Weeks, Leavesley, Welder, and Saulnier (1974)
● Upward
● Downward
○ None
White River
108°
Meeker
Layer 2 model boundary
40°
Duck Cr
Big Duck Cr
Yellow
Corral
Dry Fork
Sheep Creek
Ryan
Sprs
Snake
Greek
Sulphur
Black
Eureka
Willow
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Stewart Gl
Story Gl
Fourteenmile Cr
97
3
45
4
200
57
78
240
6
75
137
31
15
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 20.--Difference in potentiometric heads between the upper and lower aquifers.


EXPLANATION
450 ESTIMATED DISSOLVED-SOLIDS CONCENTRATIONS, IN MILLIGRAMS PER LITER
108°
40°
Meeker
White River
BOUNDARY OF PARACHUTE CREEK MEMBER
Barcus Gl
Greek
Duck Gr
Big Duck Gr
Yellow
Corral Gulch
Stake Spr Dr
Ryan Gulch
Dry Fork
Sheep Creek
Piceance Creek
Fourteenmile Gr
Black Sulphur Creek
Eureka Gr
Fawn Gr
Hunter Greek
Willow Creek
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Story Gl
450
800
800
500
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

Figure 21.—Estimated dissolved-solids concentrations in water recharging the aquifer system.

As the ground water in the upper aquifer flows away from the recharge areas, dissolved-solids concentrations increase and the water changes to a sodium bicarbonate type. Large dissolved-solids-concentration increases occur in the Uinta Formation (layer 1) where concentrations are two to three times as great as in the recharging water, and near the base of the upper part of the Parachute Creek Member (layer 2) where concentrations are 10 or more times as great as in the recharging water. The principal source of this increase appears to be the upward flow of water with large dissolved-solids concentrations from the lower aquifer into the upper aquifer. Upward flow probably accounts for the larger dissolved-solids concentrations near tract C-b and in the north-central discharge areas of the basin (figs. 20 and 24).

Increases in the dissolved-solids concentrations in the lower aquifer probably occur in three ways. First, the dissolved solids increase by dissolution of the host marlstones as water moves through the aquifer. Second, permeable zones produced by fracturing and dissolution of saline minerals near the basin margins laterally abut impermeable sections of the saline zone toward the central part of the basin. The configuration of the edges of the saline zone is highly irregular, resulting in local restrictions to horizontal and vertical flow. This restriction to flow appears to create zones of almost stagnant ground water that slowly dissolves saline minerals from the host rock. Third, water moving through fractures and solution openings in the lower part of the Parachute Creek Member can come in contact with sodium chloride and sodium bicarbonate salts in the aquifer. These soluble minerals dissolve to produce water with dissolved-solids concentrations in excess of 30,000 mg/L. Over geologic time, these processes of dissolution have produced the leached zone.

Saulnier (1978) found that the dissolution is presently most active along the edges of the main body of the saline zone. Further, dissolution in the saline zone is aided by major fractures that penetrate this section and allow circulating ground water to contact the soluble salts. This phenomenon is well displayed in a west-northwest-trending zone of fracturing along the northern margin of the basin (fig. 22). Here fractures allow saline water to move from the lower to the upper aquifer, thereby increasing the dissolved-solids concentrations in the upper aquifer. This fracture-associated dissolution is responsible for the saline springs in Alkali Flat adjacent to the lower reach of Piceance Creek and Stinking Spring along the lower reach of Yellow Creek. An analogous situation is the probable cause of the saline water pumped from wells that have been drilled through and left open to the saline zone. Saline water moving up the well bores locally contaminates water in the upper aquifer and in the alluvium. In the past, this local contamination has given an erroneous indication of the extent of saline water in the upper aquifer (Welder and Saulnier, 1978, p. 14).

Chemical Reactions

The principal chemical reactions observed in the Piceance basin are dissolution, precipitation, ion exchange, and oxidation reduction. These reactions primarily are responsible for the chemical composition of the ground water in the basin. The reactions are best described in reference to position in the ground-water flow system.

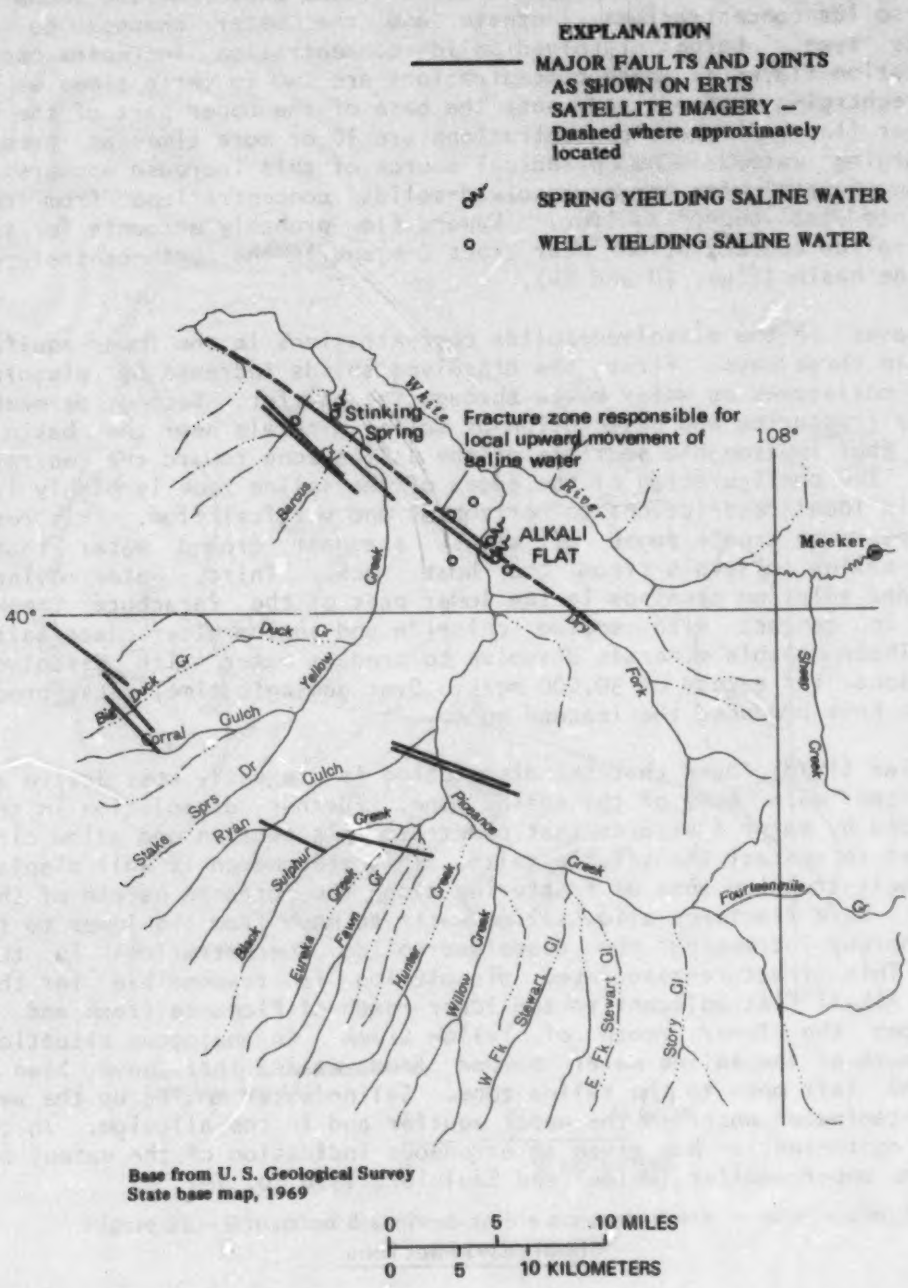

EXPLANATION
MAJOR FAULTS AND JOINTS AS SHOWN ON ERTS SATELLITE IMAGERY – Dashed where approximately located
SPRING YIELDING SALINE WATER
WELL YIELDING SALINE WATER
White River
Stinking Spring
Fracture zone responsible for local upward movement of saline water
108°
ALKALI FLAT
Meeker
40°
Barcus Creek
Duck Gr
Big Duck Gr
Yellow Creek
Corral Gulch
Dry Fork
Sheep Creek
Stake Sprs Dr
Ryan Gulch
Piceance Creek
Sulphur Creek
Black Sulphur Cr
Eureka Creek
Fawn Cr
Hunter Creek
Willow Creek
W. Fk Stewart Gl
E. Fk Stewart Gl
Stewart Gl
Story Gl
Fourteenmile Gl
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 22.—Major faults and joints in the northern part of the Piceance basin (modified from Saulnier, 1978).

Dissolution

Various dissolution reactions occur throughout the basin but specific reactions predominate at different points along the ground-water flow paths. Mineralogic analyses of samples of oil shale from the Green River Formation indicate that about 43 percent of the marlstone is composed of calcite and dolomite (Yen and Chilingarian, 1976). In the Uinta Formation, calcite and dolomite are present as cements in the sandstones and siltstones of the unit. Although these minerals do not dissolve rapidly, the chemical composition of ground water in recharge areas where marlstones are exposed indicates calcite and dolomite are going into solution. Calcium concentrations usually range from 50 to 100 mg/L and are almost double the magnesium concentrations.

Farther down the ground-water-flow path (toward the center of the basin), other dissolution reactions predominate. These reactions involve the evaporative salts, nahcolite and halite, found in the saline zone. The minerals are so soluble that they can be detected during drilling by measuring the specific conductance of water produced during drilling and comparing these data to core samples. Cores containing the salts are often of nonuniform diameter due to the differing rates of dissolution of adjacent segments of the core. Because of the small permeability of this zone (Dale and Weeks, 1978), the minerals can be dissolved only when fractures, wells, or adjacent dissolution have exposed the minerals to water. Welder and Saulnier (1978) and Dale and Weeks (1978) report that water from the leached zone in the central part of the basin, where the saline zone is thickest, has a specific conductance that ranges from 1,100 to 1,600 µmho/cm (micromhos per centimeter at 25°C). These relatively small values of specific conductance indicate that only limited dissolution is occurring at the top of the present saline zone. However, the specific conductance of water from wells near the perimeter of the saline zone indicates that large-scale dissolution occurs near the northern margin of the basin and along the edges of the saline zone. Dissolution of these sodium salts is a contributing factor in the change of water from a mixed cation bicarbonate type water to a sodium bicarbonate type water. Other factors affecting this change in water type are calcite precipitation and ion exchange, as explained in the following sections.

Precipitation

Examination of drill cores and unweathered outcrops reveals calcite deposits in fractures and vugs in the Parachute Creek Member. A fault zone in Ryan Gulch contains a 2- to 5-ft wide filling of laminated and crystalline calcite. Springs in the northern part of the basin sometimes issue from travertine mounds, and seeps on cliff faces may flow down "drapings" of calcite and travertine. These occurrences are indirect evidence that calcite is at or near saturation in most ground water in Piceance basin, even though maximum calcium concentrations are about 100 mg/L and may be as small as 10 mg/L in water from the Parachute Creek Member.

A computer program entitled WATEQ (Truesdell and Jones, 1974) was used to analyze water-quality data for the different aquifer units in the basin to determine the stability of various mineral phases in the ground-water environment. The calculations showed that calcite is at or near saturation in the majority of samples, and in nearly all samples collected away from the recharge areas. The precipitation of calcite is probably determined by the generalized reaction:

$$2\,HCO_3^{-} + Ca^{2+} \longrightarrow CaCO_3\downarrow + H_2CO_3. \quad (1)$$

In Piceance basin, the driving mechanism for such a reaction is the bicarbonate concentrations (usually greater than 300 mg/L) in the water. The bicarbonate is supplied by dissolution of carbonate minerals and nahcolite, by the sulfate-reduction reaction discussed below, and possibly by silicate hydrolysis.

Other minerals that have been observed to be precipitated secondarily are pyrite, FeS_2, and neighborite, $NaMgF_3$. Pyrite is commonly found lining vugs, filling fractures, and replacing fossil remains in rocks from the Parachute Creek Member, especially below the Mahogany zone. Hydrogen sulfide gas often is detected in wells penetrating the Parachute Creek Member, indicating that reducing conditions are present. At the levels of pH (7 to 8.8) generally measured in the Piceance basin, pyrite is stable in reduced waters. Pyrite also is found as a primary precipitate in the marlstones, indicating that the secondary minerals may represent recycled pyrite produced by past changes in alkalinity and formation temperature.

Neighborite is a rare mineral and was found only in a few samples from the northern part of the basin. The mineral consists of soft, yellow to white, translucent crystals found in vugs in the Parachute Creek Member. Very little is known about the stability of neighborite, but water in the northern parts of Piceance basin locally contains relatively large concentrations of sodium and fluoride. Plots of water types and ionic ratios calculated for this part of the basin indicate a slight enrichment in magnesium due to calcite precipitation. Larger fluoride concentrations may combine with magnesium to form the ion pair, MgF_3^{-}, prior to neighborite precipitation.

Ion Exchange

Although the changing of water from a mixed cation bicarbonate type in the recharge areas to a sodium bicarbonate type in the central discharge parts of the basin occurs in both the upper and lower aquifers, the change is more pronounced and occurs in shorter lateral and vertical distances in the Parachute Creek Member. For example, water from a spring issuing from the upper aquifer along upper Black Sulfur Creek has a calcium concentration of 61 mg/L and a sodium concentration of 45 mg/L. A sample collected from the lower aquifer at Ryan Ridge in the central part of the basin has a calcium concentration of 4.2 mg/L and a sodium concentration of 550 mg/L. Dissolution of nahcolite is a significant factor in this change in ionic proportions in areas where brines exist, but in other areas, and in the Uinta Formation, another mechanism must account for this change in ionic proportions.

The dolomitic marlstones of the Parachute Creek Member contain significant amounts of clay minerals. Dyni (1976) determined that smectite, illite, chlorite, and kaolinite occur in these rocks and that a progression of clay types occur from the basin margins to the basin center. Illite is the most common clay mineral in the Piceance basin, especially away from the saline-mineral depocenter. Ground water near the margins of the basin may have calcium concentrations of about 100 mg/L as the result of dissolution of the dolomitic marlstones. If ion exchange were taking place according to the following reaction (X indicates an exchange site):

$$Ca^{2+} + Na_2X \longrightarrow CaX + 2Na^+, \qquad (2)$$

the calcium would be removed from solution and sodium would become the dominant cation in solution. Although the calcium concentration is not excessive, preliminary geochemical-model studies indicate that ion exchange may be actively altering the water composition in the central part of the basin.

Another ion exchange mechanism involving dolomite could potentially contribute to the observed magnesium enrichment according to the following generalized reactions (X indicates an exchange site):

$$Ca\,Mg\,(CO_3)_2 + CaX \longrightarrow MgX + 2CaCO_3 \qquad (3)$$

$$MgX + 2Na^+ \longrightarrow Na_2X + Mg^{2+}. \qquad (4)$$

This series of reactions could lead to the observed precipitation of low magnesium calcite (Desborough and others, 1974) and relative magnesium enrichment in the water. Sodium concentrations in the water could remain relatively large, due to nahcolite dissolution and the calcium-sodium exchange illustrated by reaction 2.

Oxidation

Sulfur is present in ground water in Piceance basin as both oxidized and reduced species. Sulfur in the Uinta Formation is present as the oxidized sulfate ion in concentrations exceeding 500 mg/L. Oxidizing conditions exist in the Uinta Formation due to the availability of oxidized water, which occurs as precipitation recharge. In areas of upward water movement, sulfide species that migrate upward into the Uinta Formation from underlying formations are oxidized to sulfate. In other areas where upward movement of sulfur is not possible, the source of the sulfate in the Uinta Formation is unknown. Gypsum has been recorded only in discharge areas in the Uinta Formation, not in recharge areas or near the water table. In the upper parts of the Willow Creek drainage basin, springs bring water containing hydrogen sulfide gas to the surface from below the Uinta Formation. In this part of the recharge area, such upward leakage along fractures may provide the source of sulfate for the Uinta Formation.

In the Parachute Creek Member, primary and secondary pyrite minerals in the organic-rich marlstones probably provide a sulfur source when exposed to oxidized water in the recharge areas.

Reduction

Water from the organic-rich marlstones of the Parachute Creek Member often contains hydrogen sulfide gas and smaller sulfate concentrations than found in the Uinta Formation. Sulfate concentrations less than 10 mg/L are common in samples from the lower aquifer. During the drilling of 24 test holes in 1975-76, hydrogen sulfide gas commonly was released as the drill penetrated the Parachute Creek Member.

The source of sulfur in the Parachute Creek Member is not certain but the large amounts of organic material present in this unit probably help to maintain a reducing condition throughout much of Piceance basin. The most probable mechanism for sulfide production is through the generalized reaction:

$$\text{organic material} + SO_4{}^{2-} \longrightarrow H_2S + \text{carbonate species} \qquad (5)$$

Whether biogenic processes are involved in the reduction of sulfate is not clear, but the coincidence of aqueous sulfide species and organic material in the bedrock occurs throughout the basin. This reaction also would act as another contributor to the large concentrations of bicarbonate found in water from this stratigraphic unit.

Pyrite is commonly found in small quantities as a primary and secondary mineral in the Parachute Creek Member (Desborough and Pitman, 1974). This mineral is slightly soluble in warm water and may contribute small amounts of hydrogen sulfide to the water through the following reaction in a reducing environment:

$$FeS_2 + 4H^+ + 2e^- \longrightarrow 2H_2S + Fe^{2+}. \qquad (6)$$

The Fe^{2+} ion that would result from reaction 6 may be reprecipitated as the black precipitate often observed during the pumping of wells producing water from the Parachute Creek Member. The Fe^{2+} ion probably combines with the HS^- to precipitate FeS, which is unstable in the oxidizing environment that occurs when the water reaches the surface. This instability causes the precipitate to oxidize in the presence of air to form an iron oxide. Iron oxide coatings are commonly found on rocks that are exposed to the "black water" discharged from wells tapping the Parachute Creek Member.

Secondary pyrite is formed where the dissolved iron which went into solution in the recharge areas precipitates out of solution in the discharge areas. Drill cores from the Naval Oil Shale Reserve, immediately to the south of the study area, have extensive pyrite coatings in vugs and on fractures. These secondary pyrite minerals occur where ground water is close to a discharge area.

The product of the principal chemical reactions is a sodium bicarbonate water with oxidized sulfur species in the Uinta Formation and reduced sulfur species in the Parachute Creek Member. Carbonate species and, therefore, total carbon dioxide in the system are produced by atmospheric introduction via recharge, reduction of sulfur species, and dissolution of the carbonate minerals, calcite, dolomite, and nahcolite. Carbonate species are removed from the system in the northern part of the basin by calcite precipitation. Large sodium concentrations are produced by ion exchange and nahcolite and halite dissolution.

Distribution of Trace Constituents

Certain trace constituents occur in ground water in the basin in larger than normal concentrations. The relative concentrations of these constituents can be used as an aid in identifying the source of the water in springs and wells. Desborough, Pitman, and Huffman (1974) reported on the mineral residence of many of the trace constituents, and Dyni (1976) speculated that smectites and illites served as traps for trace constituents soon after the lake sediments were deposited. Other sources of trace constituents are in primary sulfide, halide, carbonate, and silicate minerals that occur in the basin sediments. The following data on the occurrence and distribution of trace constituents in ground water in Piceance basin are excerpted from Saulnier (1978).

Trace constituents that were found in less than significant concentrations were beryllium, copper, cadmium, lead, mercury, manganese, molybdenum, selenium, and zinc. Trace constituents found in significant concentrations to warrant further discussion were arsenic, barium, boron, fluoride, iron, lithium, and strontium.

Arsenic

Concentrations of dissolved arsenic in ground water in Piceance basin generally do not exceed 50 µg/L (micrograms per liter). However, concentrations of dissolved arsenic between 10 and 50 µg/L are common in water from wells tapping the Parachute Creek Member in the area between Piceance Creek and Dry Fork. Arsenic concentrations of 80 and 95 µg/L were found in water from two wells located in this area. The mineral residence of arsenic is probably authigenic sulfides in the Parachute Creek Member (Desborough and others, 1974).

Barium

Dissolved-barium concentrations greater than 500 µg/L occurred in water from about one-third of the sampled wells completed in the lower aquifer. The largest concentrations occurred in the brines found in the northern part of the basin. Barium concentrations generally are less than 500 µg/L in the upper aquifer. Hem (1970) suggests that barium concentrations generally are controlled by the solubility of barite ($BaSO_4$). The occurrence of barite as a secondary mineral in the northern part of Piceance basin has been reported (G. A. Desborough, written commun., 1975). Calculations using the WATEQ computer program indicate that the brines in the basin are slightly saturated with respect to barite and are saturated with respect to witherite ($BaCO_3$), which also occurs in the area (Milton, 1971). Barium can possibly be complexed with chloride in reduced waters (Holland, 1967), a distinct possibility in the high chloride, reducing waters of the north-central Piceance basin. Upon entering oxidized waters, the relatively insoluble barite would then precipitate as a secondary mineral, the mode of occurrence observed for barite in this study (Plummer, 1971).

Boron

Concentrations of boron greater than 5,000 µg/L are common in water samples from the lower aquifer and less common in the upper aquifer. Concentrations of this magnitude occur in water throughout the basin but are most common in the northern part of the basin where the brines occur.

Boron is commonly concentrated in evaporites, but no borate minerals have been reported in Piceance basin. Sheppard and Gude (1973) found that boron can occur in potassium feldspars of saline, alkaline, lacustrine deposits. Boron has not been identified in the feldspars of Piceance basin, but searlsite ($NaBSi_2O_6.H_2O$), reedmergnerite ($NaBSi_3O_8$), garrelsite [$(Ba,Ca,Mg)B_2SiO_6(OH)_3$], and leucosphenite ($CaBaN_3BTi_3Si_9O_{29}$) have been reported in the Green River Formation (Milton, 1971). Little is known of the solubility of these minerals. As a result the mineral source of the boron in solution in Piceance basin is unknown at present.

Fluoride

The distribution of dissolved fluoride in the upper and lower aquifers can be described in relation to the abundance of dissolved calcium as well as the presence of fluoride minerals. The amount of fluoride ion theoretically in solution at equilibrium can be determined by the solubility product of fluorite (CaF_2):

$$K_{sp}=(Ca^{2+})(F^-)^2. \tag{7}$$

Because the fluoride activity is squared, small calcium concentrations would allow large fluoride concentrations to be present in the water. The equilibrium concentration of dissolved calcium fluoride is 15 mg/L at 18°C. The average concentrations are 38 mg/L for calcium and 1.1 mg/L for fluoride in water from the Uinta Formation, 18 mg/L for calcium and 7.1 mg/L for fluoride in water from the upper part of the Parachute Creek Member, and 10 mg/L for calcium and 22 mg/L for fluoride in water from the lower part of the Parachute Creek Member. Larger concentrations of calcium in water from the Parachute Creek Member would result in the precipitation of fluorite. The reduction of calcium concentrations due to ion exchange and calcite precipitation are, thus, important factors in maintaining the observed large concentrations of fluoride.

Authigenic cryolite (Na_3AlF_6), fluorite (CaF_2), fluorapatite [$Ca_5(PO_4)_3F$], and neighborite ($NaMgF_3$) are present in the Parachute Creek Member (Charles Milton, written commun., 1974). Calculations using the WATEQ computer program indicate that the water is undersaturated with respect to both fluorite and cryolite; thus, these minerals probably are dissolving rather than precipitating. As a result, the large proportion of fluoride in cryolite could add significantly to the dissolved-fluoride concentrations found in the ground water. Little is known about the kinetics of dissolution of these minerals in the presence of water containing relatively small concentrations of calcium and relatively large concentrations of sodium.

The original source of the fluoride is uncertain. The fluoride may have been added to Lake Uintah by hot springs or volcanic ash. Devitrified tuffaceous lenses are common in the Green River Formation. Evaporation from the lake could have concentrated the fluoride sufficiently to form authigenic fluoride minerals and allow the inclusion of the fluoride ion in clay minerals. After induration and basin deformation, circulating ground water reversed the process, allowing relatively large concentrations of fluoride to be present in the water. At some time after resolution of the fluoride, neighborite ($NaMgF_3$) precipitated in vugs. It appears likely that the formation of MgF_3^- complexes precedes neighborite precipitation. As in the calcium fluoride example above, the solubility product indicates that relatively small magnesium concentrations would be required to maintain the relatively large fluoride concentrations. In the lower aquifer the smallest concentrations of dissolved magnesium are found to coincide with the largest concentrations of dissolved fluoride, as required by the solubility product calculations.

The absence of significant concentrations of dissolved fluoride in the Uinta Formation is due to the combination of relatively larger calcium concentrations than in the Parachute Creek Member and the absence of a source of fluoride in the sediments or in authigenic minerals. Near some fractures, faults, and improperly constructed wells, water in the alluvial aquifer and the Uinta Formation has unusually high concentrations of fluoride for this formation. These relatively larger concentrations occur in the northern part of the basin where the potentiometric head allows upward movement of water from the Parachute Creek Member.

Iron

Water with more than 300 µg/L of dissolved iron is common in the upper aquifer. The sandstones and siltstones of the Uinta Formation have ironstone concretions throughout. These concretions probably are the major source for much of the dissolved iron.

The Parachute Creek Member contains variable amounts of authigenic pyrite (Trudell and others, 1970). In the recharge areas and in the warm bicarbonate water found in the lower aquifer, where the pH normally ranges from 7.5 to 8.5, pyrite either can be dissociated to form ferrous ions in solution, or the ferrous ion can combine with carbonate to form siderite and ferroan [$(Mg,Fe)CO_3$]. The presence of siderite and ferroan are commonly reported in the Parachute Creek

Member (Desborough and others, 1974; Robb and Smith, 1974). Relatively small concentrations of iron occur in water in the Parachute Creek Member, indicating that most dissolved iron may be reprecipitated as carbonate. As noted above, the "black water" produced from many wells in the Parachute Creek Member indicates that some ferrous iron remains in solution and is carried into wells and subsequently precipitated as FeS.

Lithium

Concentrations of dissolved lithium are greater than 100 µg/L in water samples from wells that contain brines. Relatively large concentrations of lithium also are associated with water that has relatively small dissolved-solids concentrations but relatively large concentrations of other trace constituents. The largest concentrations of lithium occur in samples from wells in the central part of the basin. Dissolved-lithium concentrations, as much as 39 and 42 mg/L, have been reported in water from these wells. Desborough, Pitman, and Huffman (1974) did not find a likely mineral residence for lithium but indicated that fluoride and lithium show a positive correlation in water samples from the Piceance basin reported in Ficke, Weeks, and Welder (1974). Relatively large lithium concentrations also are associated with relatively large concentrations of bicarbonate. The lithium may occur in the evaporite minerals of the Parachute Creek Member either as a carbonate or a chloride. In addition, lithium may be adsorbed on clays. It is possible that in predominantly sodium waters sodium could exchange for adsorbed lithium in smectites and illites. Because these same waters also have relatively small calcium concentrations and consequently relatively large fluoride concentrations, the result would be a positive lithium-fluoride correlation.

Strontium

Strontium is a significant trace constituent in the upper aquifer system, especially in the Uinta Formation and its associated marlstone tongues. In samples from springs in drainage basins tributary to Piceance Creek, strontium concentrations increase downgradient in a distance of 10 to 15 mi. Thus minerals containing strontium probably are being dissolved by the circulating ground water. Calculations using the WATEQ computer program indicate the water generally is supersaturated with respect to strontianite ($SrCO_3$) but not with respect to celestite ($SrSO_4$). However, celestite is rarely reported in mineral analyses in Piceance basin.

The strontianite supersaturation indicates a precipitation reaction that is very slow. Thus, the strontium in solution could be dissolved from carbonates or sulfates in the first few miles of the flow system and remain dissolved in the water, accumulating due to a slow rate of mineral precipitation. The original source of the strontium in the Uinta Formation is unknown, but it is possible that strontium occurs in the carbonate cements or as accessory sulfate in the Uinta Formation.

THE SIMULATED HYDROLOGIC SYSTEM

Mining of oil shale from tracts C-a and C-b will require water to be pumped from the mines in order to prevent flooding. The pumping could cause water-level declines in the aquifers and reduce the rate of ground-water discharge to streams near the mines. In addition, the pumping could alter the location of ground-water flow paths, thereby producing changes in the chemical quality of the water in the aquifers and in local streams. Spent shale also could become a source of ground-water quality degradation once the mining intervals have been exhausted, and the mine retorts containing the spent shale become flooded. Studies by Ward, Margheim, and Lof (1971) and Schmidt-Collerus (1974) indicate that between 1 and 5 percent of the spent shale may be water-soluble saline minerals. For example, on abandoning tract C-b, the volume of saline minerals in the spent shale might range from 30 to 150 million tons and could, thus, have a serious long-term impact on the water quality near the abandoned mine. Mathematical-modeling techniques may be used to evaluate the possible effects of various mine-pumping practices and subsequent mine flooding. Weeks, Leavesley, Welder, and Saulnier (1974) and Sokol (1976) determined some of the possible effects of mine dewatering on the water levels in the upper and lower aquifers in Piceance basin; however, they did not study the water-quality changes that may accompany the mining activities.

Model Description

In order to simulate the possible effects of the mines on ground-water quality, a three-dimensional mathematical model that simulates solute transport through the ground-water system was constructed. The model is based on a finite-difference solution technique developed for the U.S. Geological Survey by INTERCOMP, Inc. (1976). The model simulates confined, density-dependent flow, and solute transport with dispersion in nonhomogeneous, anisotropic aquifers with irregular geometry under steady- or transient-flow conditions. The model simulates movement of a conservative solute (dissolved-solids concentrations) with dissolution as the only chemical reaction term. As a result, the complex geochemical system in the basin can only be simulated to the extent that the geochemistry affects the dissolved-solids concentrations in the aquifer. This is not a severe restriction, however, because dissolution of evaporite minerals in the saline zone and dissolution in the unsaturated zone are the predominant chemical reactions occurring in the basin and these reactions dominate the effects of the other geochemical reactions. The basic equations that describe the ground-water flow and material balance of the solute have pressure and concentration as the primary dependent variables. The independent variables include: (1) Time; (2) aquifer characteristics, such as hydraulic conductivity, aquifer extent and thickness, porosity, compressibility, solubility, and dispersivity; (3) fluid characteristics, such as concentration, density, compressibility, viscosity, and flux rate; and (4) related initial and boundary conditions.

The node network used in the Piceance basin model consists of a 9-by 14-cell array for each of the five layers considered in the model. The lateral model boundary for any individual layer may vary from the boundary of an adjacent layer, due to the differences in the lateral extent of the layer in each depth interval.

The hydrologic-model parameters are described at each node in the model area. The thickness of each model layer corresponds to the saturated thickness shown on figures 5, 7, 8, 9, and 11. The hydraulic-conductivity values assigned to the x, y, and z components for each model layer are shown on figures 12 to 17. The porosity, potentiometric-head, ground-water quality, and specific-storage data discussed previously also were used to define the independent variables of the model.

Dissolution was simulated by using the ground-water recharge sources in the model program to supply mass to the aquifer. The rate at which the mass was supplied corresponds to the rate of dissolution.

Model Calibration

In order to assure that the model calculations are correct, a calibration procedure was used to check the model-calculated potentiometric heads and dissolved-solids concentrations against the corresponding measured values. Because only minimal ground-water development has occurred as of 1977, the present potentimometric heads and dissolved-solids concentrations are representative of the long-term ground-water conditions in the basin. Because of the lack of transient-flow conditions in the basin, a steady-flow calibration of the model was the only calibration check possible. In this type of calibration, the model is used to simulate the long-term water-level and water-quality conditions that would result from an undisturbed natural environment. These model results are then compared to the measured data as a check of the simulation capability of the model. A disadvantage of this type of calibration is that the specific storage of the aquifers cannot be tested in the model. However, if subsequent model simulations represent long-term equlibrium conditions, the specific storage will not affect the model results.

Model simulations made using different values of dispersivity indicated that the best model results were obtained when the simulated dispersion equaled the numerical dispersion due to space- and time-truncation errors. Subsequent model simulations were made using zero-longitudinal and transverse-dispersivity factors with dispersion due only to truncation error in the backward finite-difference approximation in space and time. This approach appears to be reasonable for two reasons. First, as the node size and scale of a solute-transport model increases, the model results become less sensitive to dispersivity (Robson, 1974). Because of this, similar model-concentration distributions can be obtained using very different values of model dispersivity. Second, test simulations were made using a centered in space and time finite-difference approximation (which produces no numerical dispersion) and the backward in space and time approximation (which produces numerical dispersion). Comparison of these two simulations indicated that, at the node sizes used in the Piceance basin model, the effects of numerical dispersion would not adversely affect the concentration distribution. The centered in space and time approximation could not be used in the Piceance basin model, due to problems of solution stability inherent in this technique.

The equilibrium potentiometric heads calculated by the model for layers 1 and 5 are compared in figure 23 to the measured potentiometric heads in the upper and lower aquifers (figs. 18 and 19). The best agreement between calculated and measured potentiometric heads occurs in model layer 1 where calculated heads are within 10 ft of measured heads at 77 of the 86 model nodes in this layer. The degree of agreement is due partly to the effect of the stream valleys of Piceance and Yellow Creeks that tend to control the water levels in the upper aquifer near the valleys. The deeper the model layer is below the stream valleys, the less effect the valleys have on the potentiometric head in the layer. As a result, the calculated potentiometric heads in layer 5 are within 10 ft of the measured potentiometric heads at only 39 of the 104 nodes in this layer (fig. 23). The model-calculated potentiometric-surface maps for layers 2 and 4 are nearly identical to the potentiometric-surface maps based on measured data shown on figures 18 and 19, indicating that the model is able to produce a reasonable simulation of equilbrium potentiometric-head conditions. This agreement is further indicated by the comparison of measured and calculated potentiometric-head differences across the Mahogany zone shown on figure 20. In the areas of greatest potentiometric-head difference, away from Piceance Creek and Yellow Creek valleys, the agreement between measured and calculated data is good. There is less agreement near the streams where only slight potentiometric-head differences occur across the Mahogany zone.

Because the model calculates dissolved-solids concentrations in addition to potentiometric heads, the calibration procedure also compared measured and calculated concentration data. The measured and model-calculated dissolved-solids concentrations for each of the five model layers are shown on figures 24 to 28. Attempts to manually draw lines of equal concentration based on the measured data shown on the left of figures 24 to 28 have met with only limited success. The data points, although fairly numerous, apparently are not adequate to properly define the extent of areas of equal concentration. The reason for this difficulty became apparent when the model results were mapped. As shown on the right side of the figures, the calculated dissolved-solids distribution is multimodal, showing many areas of high and low concentration in the basin. This complex distribution is difficult to define, based only on the measured data available. When a comparison is made between the measured and calculated dissolved-solids concentrations, a reasonable degree of agreement is evident. The best agreement between the measured and calculated values occurs in layer 5. This is significant because the rate of dissolution at the saline zone has a controlling effect on the concentration distribution in layer 5. Thus, the dissolution rate simulated in the model must be reasonably correct in order for the calculated dissolved-solids concentrations in layer 5 to agree with the measured data.

A third calibration check on the simulation ability of the model involved a comparison of the measured and calculated quantity and chemical quality of water recharging to or discharging from the aquifer system. These data are shown in table 2 with dissolved-solids concentrations expressed in terms of pounds of salt per day.

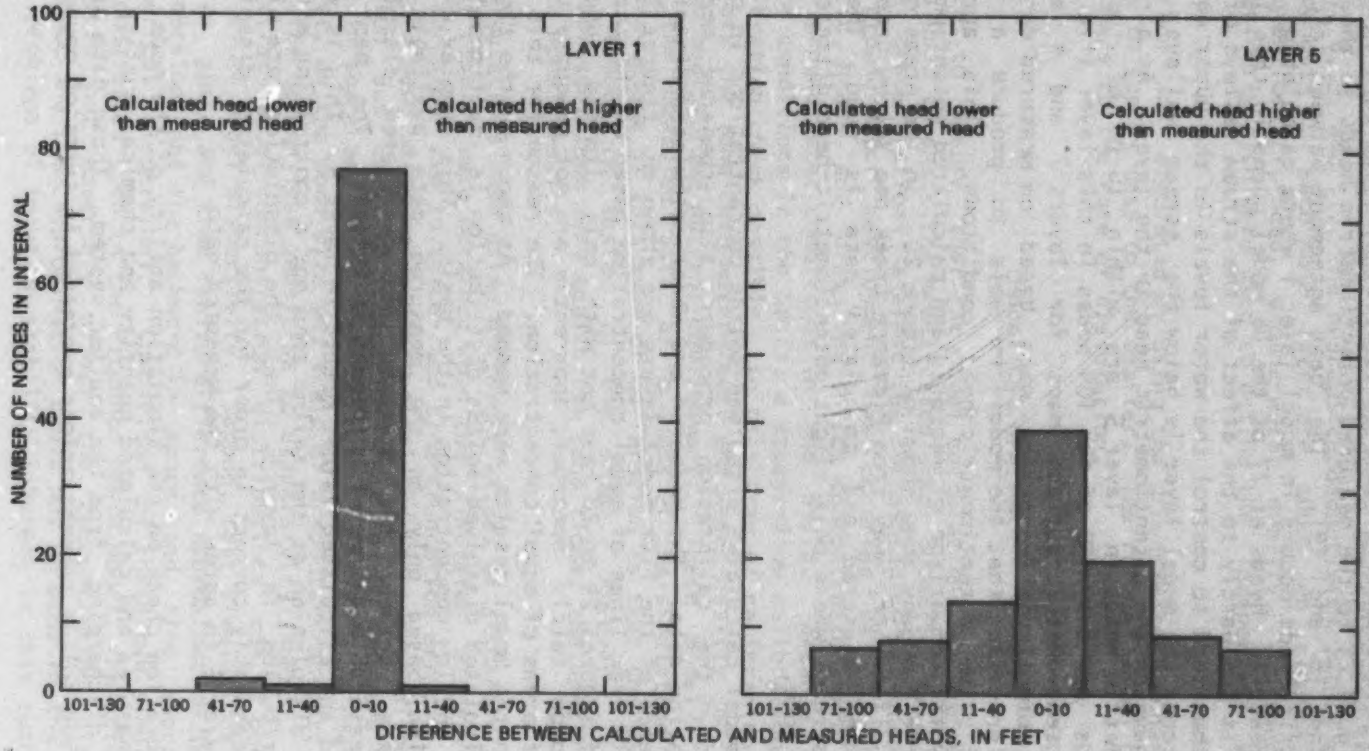


Figure 23.--Distribution of differences between calculated and measured values of potentiometric head for layers 1 and 5.

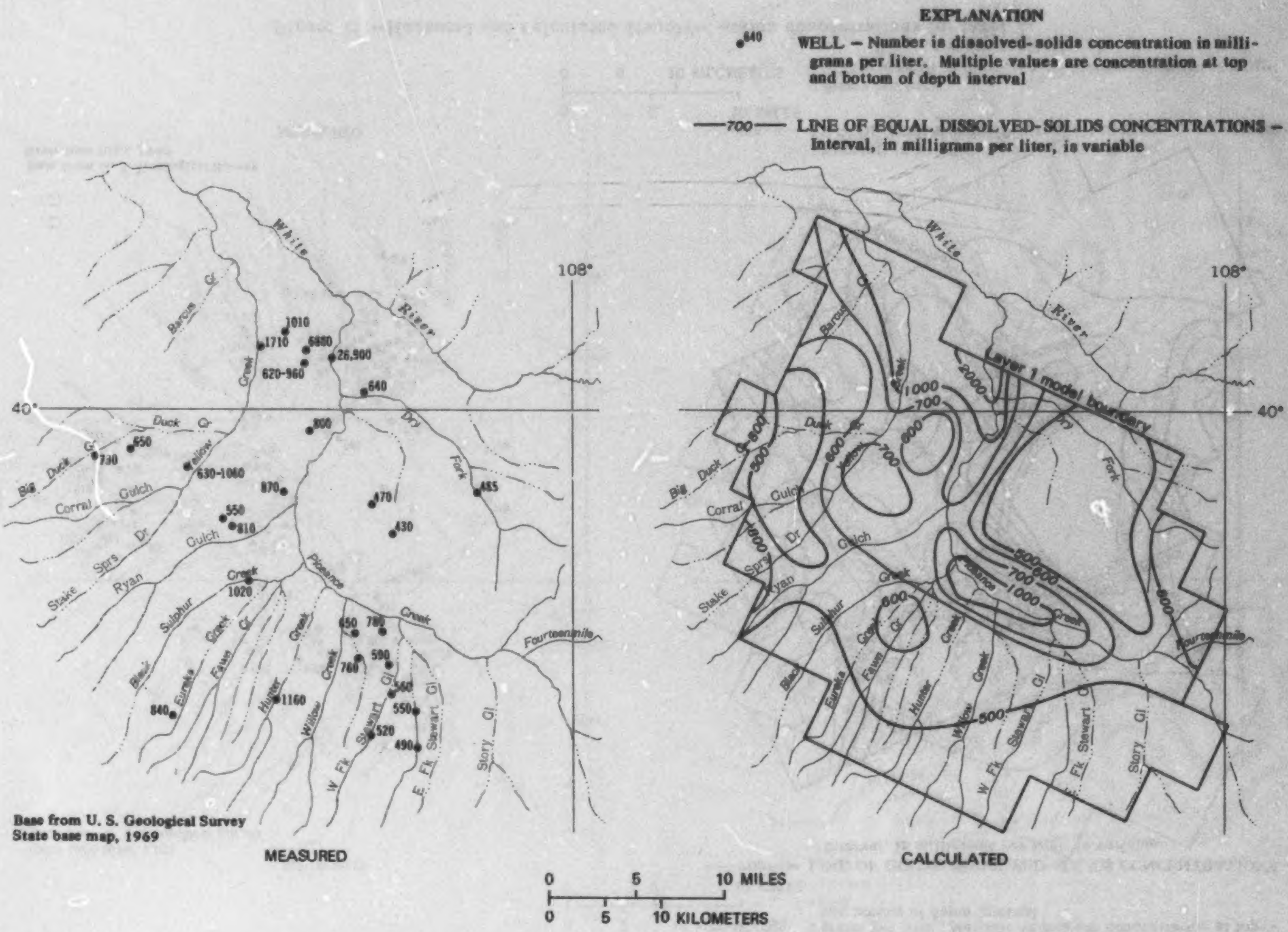

EXPLANATION
640 WELL – Number is dissolved-solids concentration in milligrams per liter. Multiple values are concentration at top and bottom of depth interval
700 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
108°
40°
White
River
Barcus
Gr
Creek
Duck
Big
Yellow
Corral
Gulch
Dry
Fork
Stake
Sprs
Dr
Ryan
Sulphur
Piceance
Creek
Black
Eureka
Fawn
Hunter
Willow
W Fk
Stewart
Gl
E Fk
Stewart Gl
Story Gl
Fourteenmile
1010
1710
6880
620-960
26,900
640
800
650
730
630-1060
870
550
810
470
455
430
1020
650
780
760
590
560
550
520
490
1160
840
Base from U. S. Geological Survey
State base map, 1969
MEASURED
Layer 1 model boundary
2000
1000
700
600
500
800
CALCULATED
0
5
10 MILES
0
5
10 KILOMETERS

Figure 24.--Measured and calculated dissolved-solids concentrations for layer 1.

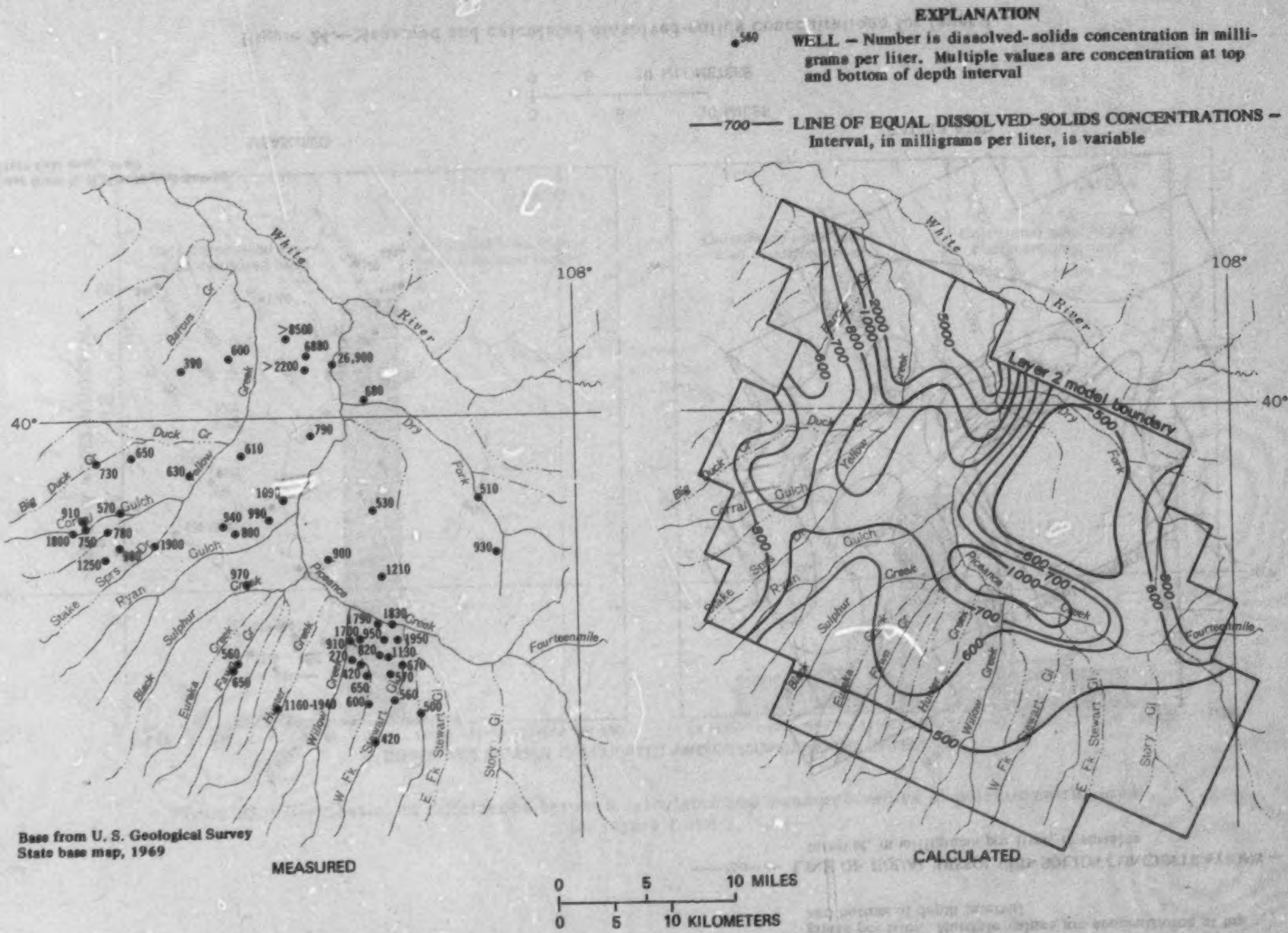
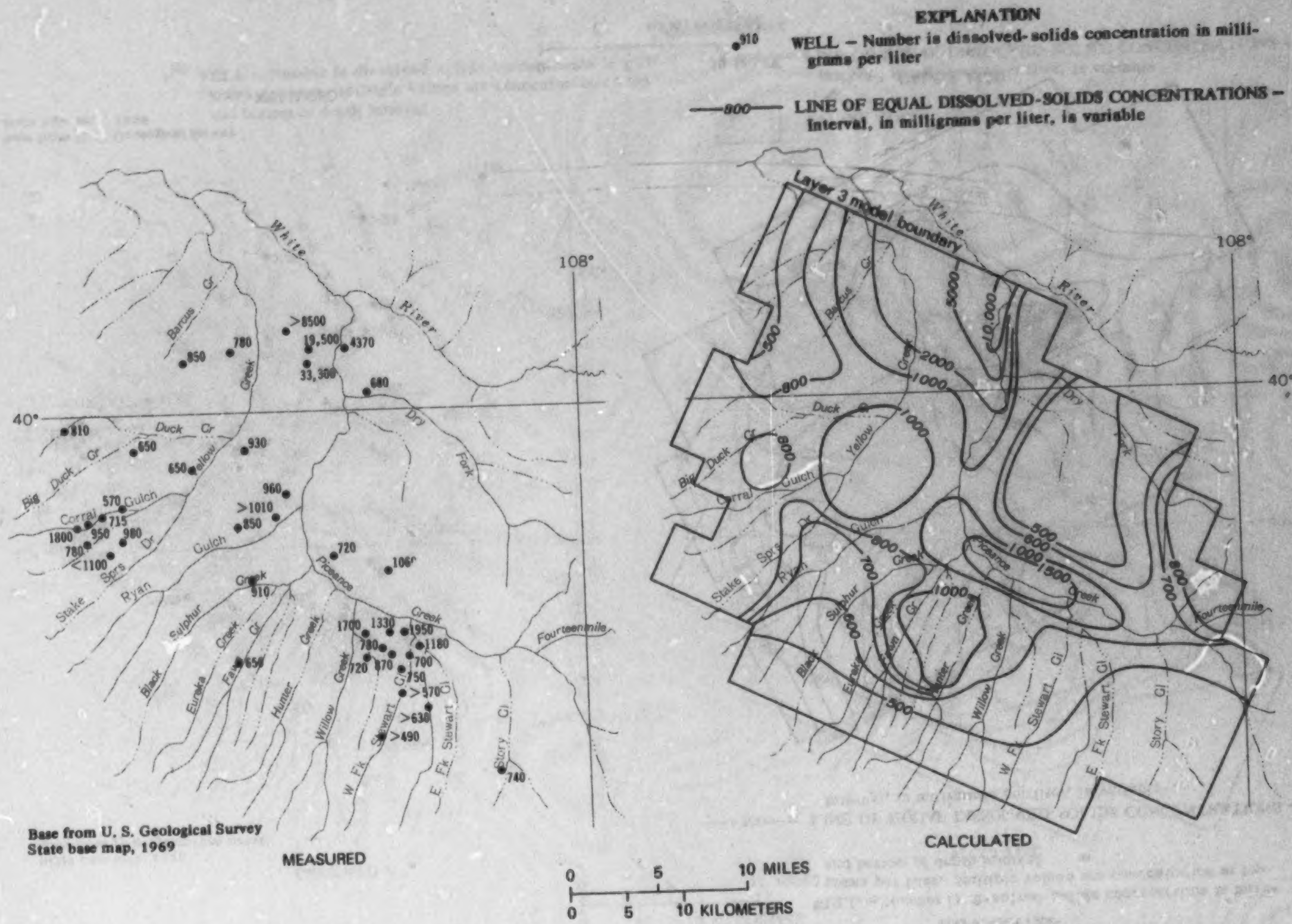
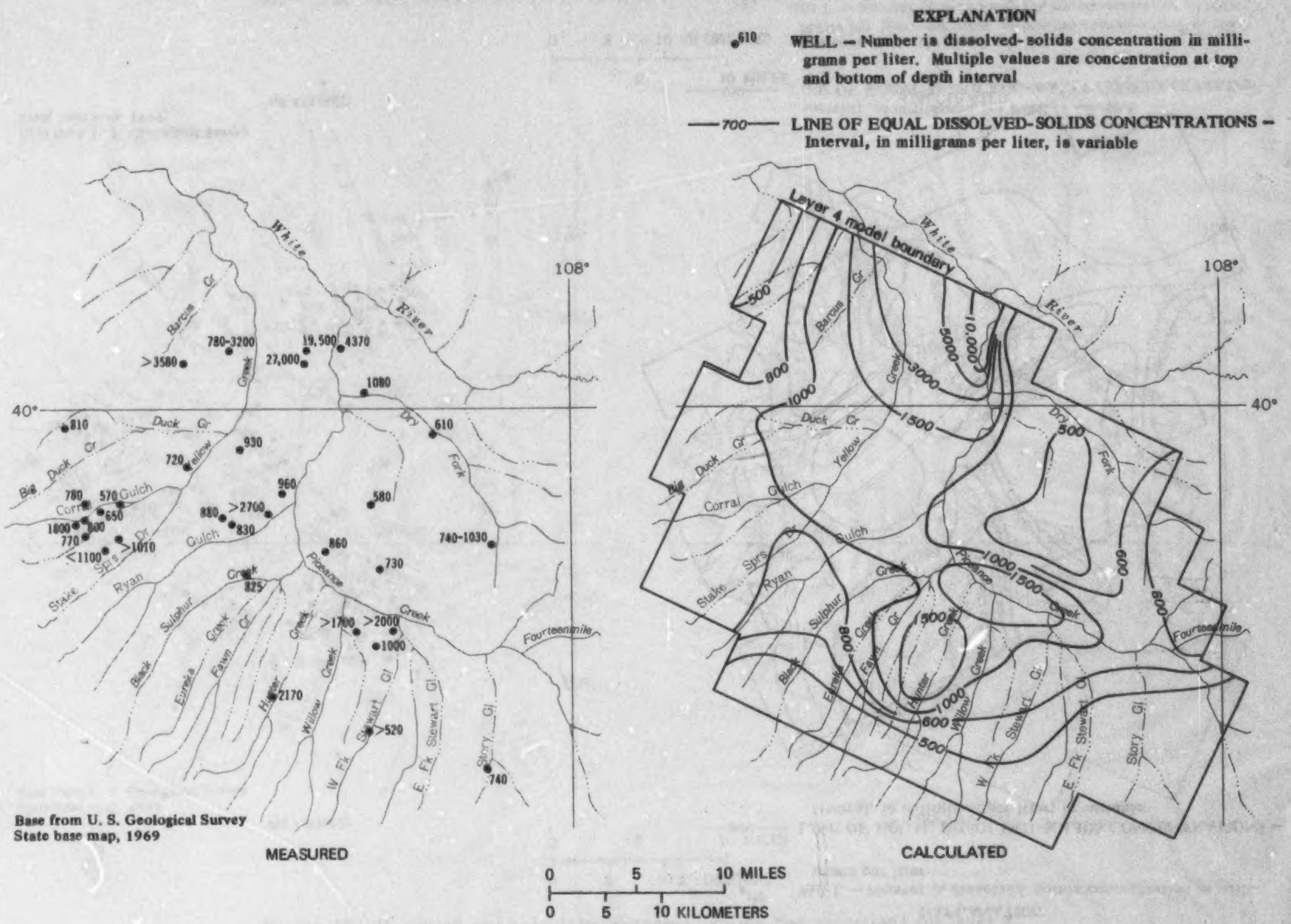

EXPLANATION
560 WELL – Number is dissolved-solids concentration in milligrams per liter. Multiple values are concentration at top and bottom of depth interval
700 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
108°
40°
White
River
Dry
Fork
Duck Cr
Big Duck Gl
Corral Gulch
Yellow
Barcus Cr
Greek
Picenace
Creek
Sprs
Stake
Ryan
Sulphur
Black
Eureka
Fawn
Hunter
Willow
W Fk Stewart Gl
E Fk Stewart Gl
Story Gl
Fourteenmile
>8500
6880
26,900
>2200
600
390
680
790
650
730
630
610
1097
530
510
910
570
780
1800
750
1900
1250
940
990
800
900
1210
930
970
1790
1830
1700
950
1950
910
820
1130
270
670
420
570
650
560
600
500
420
560
650
1160-1940
Base from U. S. Geological Survey State base map, 1969
MEASURED
Layer 2 model boundary
5000
2000
1000
800
700
600
500
1000
CALCULATED
0 5 10 MILES
0 5 10 KILOMETERS

Figure 25.—Measured and calculated dissolved-solids concentrations for layer 2.


EXPLANATION
910 WELL – Number is dissolved-solids concentration in milligrams per liter
800 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
MEASURED
CALCULATED
108°
40°
White River
Dry Fork
Barcus Cr
Greek
Duck Cr
Big Duck Cr
Yellow
Corral Gulch
Gulch
Sprs Dr
Stake Sprs
Ryan
Sulphur Creek
Black
Eureka
Fawn Cr
Hunter
Willow Creek
Piceance Creek
W Fk Stewart Gl
E Fk Stewart Gl
Story Gl
Fourteenmile
Layer 3 model boundary
>8500
19,500
4370
33,300
680
780
850
810
650
930
650
570
715
1800
950
980
780
<1100
960
>1010
850
720
1060
910
650
1700
1330
1950
1180
780
700
720
870
750
>570
>630
>490
740
500
800
1000
2000
5000
10,000
600
1500
700
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 26.–Measured and calculated dissolved-solids concentrations for layer 3.


EXPLANATION
610 WELL – Number is dissolved-solids concentration in milligrams per liter. Multiple values are concentration at top and bottom of depth interval
700 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
MEASURED
CALCULATED
Layer 4 model boundary
White River
108°
40°
Barcus Cr
Duck Cr
Big Duck Cr
Yellow
Corral Gulch
Stake Sprs Dr
Ryan Gulch
Sulphur Creek
Eureka Creek
Black
Fawn Cr
Hunter
Willow Creek
W Fk Stewart Gl
E Fk Stewart Gl
Story Gl
Piceance Creek
Dry Fork
Fourteenmile
>3580
780-3200
27,000
19,500
4370
1080
610
810
720
930
960
580
740-1030
860
730
780
570
650
1800
800
770
<1100
>1010
880
>2700
830
825
>1700
>2000
1000
2170
>520
740
500
800
1000
1500
3000
5000
10,000
600
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

Figure 27.--Measured and calculated dissolved-solids concentrations for layer 4.

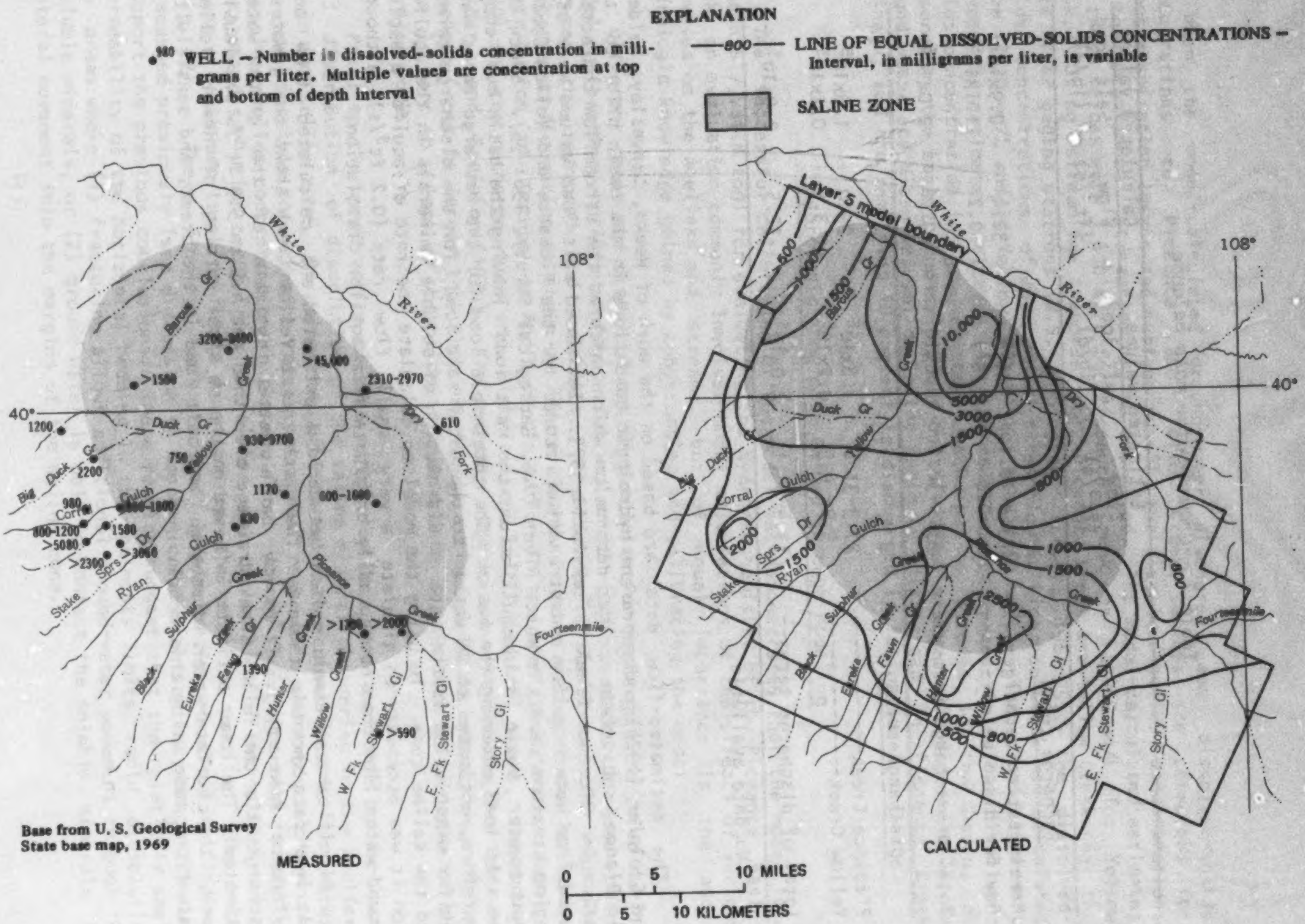

EXPLANATION
980 WELL – Number is dissolved-solids concentration in milligrams per liter. Multiple values are concentration at top and bottom of depth interval
800 LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
SALINE ZONE
White
River
108°
40°
Duck Gr
Yellow
Barcus Gr
Creek
Dry
Fork
Big Duck Gr
Corral
Gulch
Sprs Dr
Stake
Ryan
Sulphur
Piceance
Creek
Black
Eureka
Fawn Creek Gr
Hunter
Willow Creek
W Fk Stewart Gl
E Fk Stewart Gl
Story Gl
Fourteenmile
3200-8000
>1500
>45,000
2310-2970
610
1200
2200
750
930-9700
1170
600-1000
980
800-1800
800-1200
>5080
1500
>2300
>3060
830
1390
>1200
>2000
>590
Layer 5 model boundary
500
1000
1500
10,000
5000
3000
800
2000
2500
Base from U. S. Geological Survey State base map, 1969
MEASURED
CALCULATED
0 5 10 MILES
0 5 10 KILOMETERS

Figure 28.–Measured and calculated dissolved-solids concentrations for layer 5.

Table 2.--*Ground-water mass balance*

	Estimated values		Calculated values	
	Flow (ft^3/s)	Salt load (lb/d)	Flow (ft^3/s)	Salt load (lb/d)
Recharge terms				
Precipitation recharge----	33.4-36.1	(1)	32.4	0.9×10^5
Aquifer dissolution-------	0.0	(1)	0.2	1.1×10^5
Total of recharge terms---	33.4-36.1	2.0×10^5	32.6	2.0×10^5
Discharge terms				
Piceance Creek------------	27.3-31.6	1.8×10^5	29.0	1.8×10^5
Yellow Creek--------------	5.9- 4.5	0.2×10^5	3.5	0.2×10^5
Total of discharge terms--	33.4-36.1	2.0×10^5	32.5	2.0×10^5

[1] No data available.

The estimated-flow data are based on the work of Weeks, Leavesley, Welder, and Saulnier (1974) and represent hydrologic conditions in the basin prior to the Rio Blanco subsurface nuclear detonation which altered the streamflow characteristics in Piceance Creek after April 1973. Estimated salt-load values were computed from water-quality and streamflow records for the Piceance and Yellow Creeks gaging stations near the White River (U.S. Geological Survey, 1961-75). Since the ground-water basin is in equilibrium, the salt load leaving the basin must equal the salt load entering the basin. The total salt load for the recharge terms was, therefore, estimated to be equal to the total salt load for the discharge terms. Aquifer dissolution is the rate of dissolution of soluble minerals in the aquifer and the saline zone. In using the model to calculate the rate of aquifer dissolution it was necessary to simulate a very small flow rate (0.2 ft^3/s), although ground-water flow does not actually originate from aquifer dissolution.

Significant agreement exists between the estimated and calculated flow and salt-load data shown in table 2. The discharge to Yellow Creek shows the greatest difference; however, 3.5 ft^3/s may be a better estimate of the ground-water discharge to the Yellow Creek drainage area than the 4.5 to 5.9 ft^3/s previously estimated. The lower estimate is based on the physical setting of lower Yellow Creek, the surface-water discharge and salt load in the creek, and sensitivity evaluations made using this model.

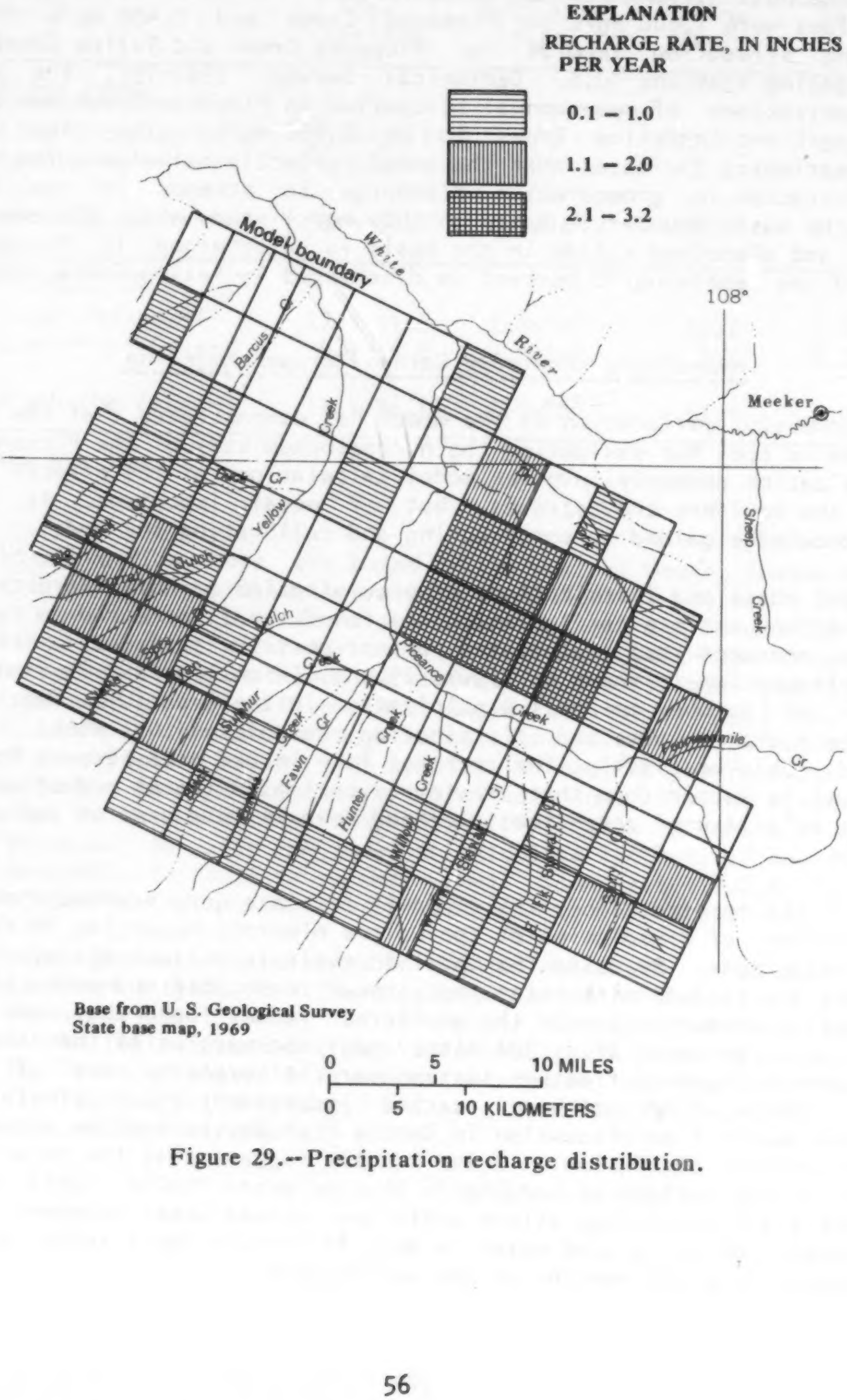
When the model-calculated ground-water discharge and dissolved-solids concentrations to Piceance and Yellow Creek valleys are corrected for evapotranspiration losses and surface runoff, the dissolved-solids concentrations of the mean-annual streamflow may be estimated. The model-calculated estimates for these values were 1,600 mg/L for Piceance Creek and 2,400 mg/L for Yellow Creek. Using streamflow records for Piceance Creek and Yellow Creek near the White River gaging stations (U.S. Geological Survey, 1961-75), the dissolved-solids concentrations of mean-annual streamflow in Piceance Creek was calculated to be 1,620 mg/L and in Yellow Creek to be 2,450 mg/L. The close agreement between the estimates indicates that the model correctly calculates the dissolved-solids concentration in ground-water discharge to streams in the basin, as measured at the basin boundary. Based on this model study about 90 percent of the ground water and dissolved solids in the basin is discharged in Piceance Creek drainage, and the remaining 10 percent is discharged in Yellow Creek drainage.

Hydrologic Knowledge Gained Through Modeling

The successful calibration of the model has demonstrated that the model is a reasonably valid tool for evaluating the hydrogeochemistry of the Piceance basin. Such an evaluation commonly involves model calculations of the effects of various stresses on the aquifers and streams, but of equal importance is the added hydrologic knowledge gained by constructing and calibrating the model.

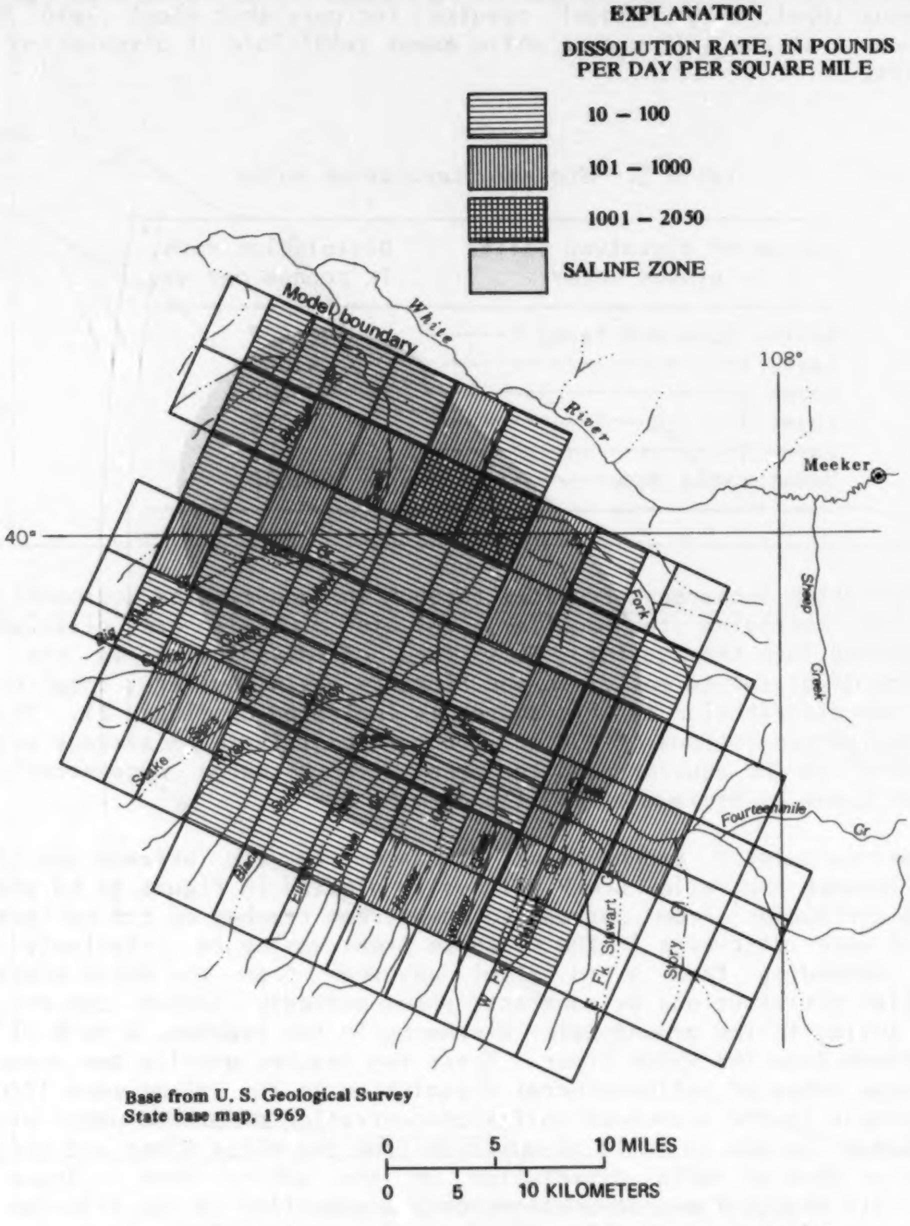
Different rates and distributions of precipitation recharge were tried during model calibration, until a configuration was found that produced a good match between the measured and calculated potentiometric surfaces. The resulting recharge configuration is shown on figure 29 and, in most areas, is similar to the distribution of October to April precipitation in the area (U.S. Weather Bureau, 1960) and the recharge rates and distribution calculated by Weeks, Leavesley, Welder, and Saulnier (1974). The recharge rate in the area between Dry Fork and Piceance Creek is larger than that previously estimated (Weeks and others, 1974), due in part to a lack of potentiometric-head data in this area at the time of the earlier work.

Prior to the construction of this model, few data were available on the rate and distribution of dissolution of the saline minerals occurring in the aquifers or in the saline zone. By using the model to evaluate various dissolution rates, it was possible to determine rates that appear reasonable and produce the proper dissolved-solids concentration in the aquifers. It was found that the areas of greatest dissolution occur (fig. 30) either near the margins of the saline zone or along a northwest-trending fracture system near the northern part of the basin (fig. 22). These findings were reached independently of similar findings discussed previously (see discussion in Geochemical System section, page 32) and support the previous conclusions. These results suggest that the relatively small permeability of the horizontal bedding in the sediments limits rapid dissolution to areas where (1) fracturing allows additional ground-water movement through the soluble minerals, or (2) ground water is able to contact the soluble minerals by lateral movement into the margins of the saline zone.


EXPLANATION
RECHARGE RATE, IN INCHES PER YEAR
0.1 – 1.0
1.1 – 2.0
2.1 – 3.2
Model boundary
White River
108°
40°
Meeker
Barcus Gr
Creek
Yellow
Rock Gr
Gulch
Piceance
Creek
Sheep Creek
Sulphur
Fawn
Gr
Hunter
Creek
Willow
Parachute
Cr
Gr
Spring
Stewart
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 29.--Precipitation recharge distribution.


EXPLANATION
DISSOLUTION RATE, IN POUNDS PER DAY PER SQUARE MILE
10 – 100
101 – 1000
1001 – 2050
SALINE ZONE
Model boundary
White
River
108°
Meeker
40°
Fork
Sheep
Creek
Fourteenmile
Gr
Stewart
Story
W Fk
E. Fk.
Snake
0
5
10 MILES
0
5
10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 30.--Rate of dissolution of saline minerals at the base of the aquifer system.

The rate of dissolution occurring in the aquifers was found to be much less than the dissolution rate at the saline zone (table 3). This is consistent with core-drilling results that commonly show negligible saline-mineral content above the saline zone (Dyni, 1974). Model results indicate that about 1×10^5 lb/d of dissolution occurs at the saline zone while about 7×10^3 lb/d of dissolution occurs in the aquifers.

Table 3.--*Mineral-dissolution rates*

Source of dissolved solids in ground water	Dissolution rate, in pounds per day
Saline zone and layer 5------	100,000
Layer 4---------------------	4,000
Layer 3---------------------	300
Layer 2---------------------	2,000
Layer 1---------------------	600
Unsaturated zone-------------	90,000

As precipitation recharge percolates through the unsaturated sediments of the Uinta Formation overlying the aquifer, soluble minerals are dissolved and ultimately carried into the aquifer. This form of dissolution is the second largest source of dissolved solids in the Piceance basin aquifers, totaling about 9×10^4 lb/d. The distribution of this source is indicated on figure 21. The areas with recharge concentrations of 450 and 800 mg/L contribute an average salt load of 240 $(lb/d)/mi^2$ to the aquifers and the area with recharge concentrations of 500 mg/L contributes an average of 150 $(lb/d)/mi^2$.

The model-calculated ground-water discharge to the streams and alluvial aquifers in Piceance and Yellow Creek valleys is plotted in figure 31 to show the cumulative distribution from upstream to downstream reaches of the valleys. The rate of ground-water discharge in the Piceance Creek valley is relatively steady in a reach extending from 4 to 31 mi upstream from the White River. The dissolved-solids distribution, by contrast, shows markedly larger concentrations of dissolved solids in the ground-water discharge in two reaches, 0 to 9 mi and 24 to 28 mi upstream from the White River. These two reaches overlie two areas with relatively large rates of saline-mineral dissolution in the saline zone (fig. 30). A similar increase in the dissolved-solids concentration of ground-water discharge to Yellow Creek occurs 10 to 14 mi upstream from the White River and this reach also overlies an area of rapid dissolution in the saline zone. These model results indicate that, if evapotranspiration and underflow in the alluvium can be accounted for, it might be possible to make an onsite determination of the relative rate of saline-mineral dissolution in the saline zone simply by monitoring changes in the quality of surface water during relatively low flows along Piceance or Yellow Creeks.

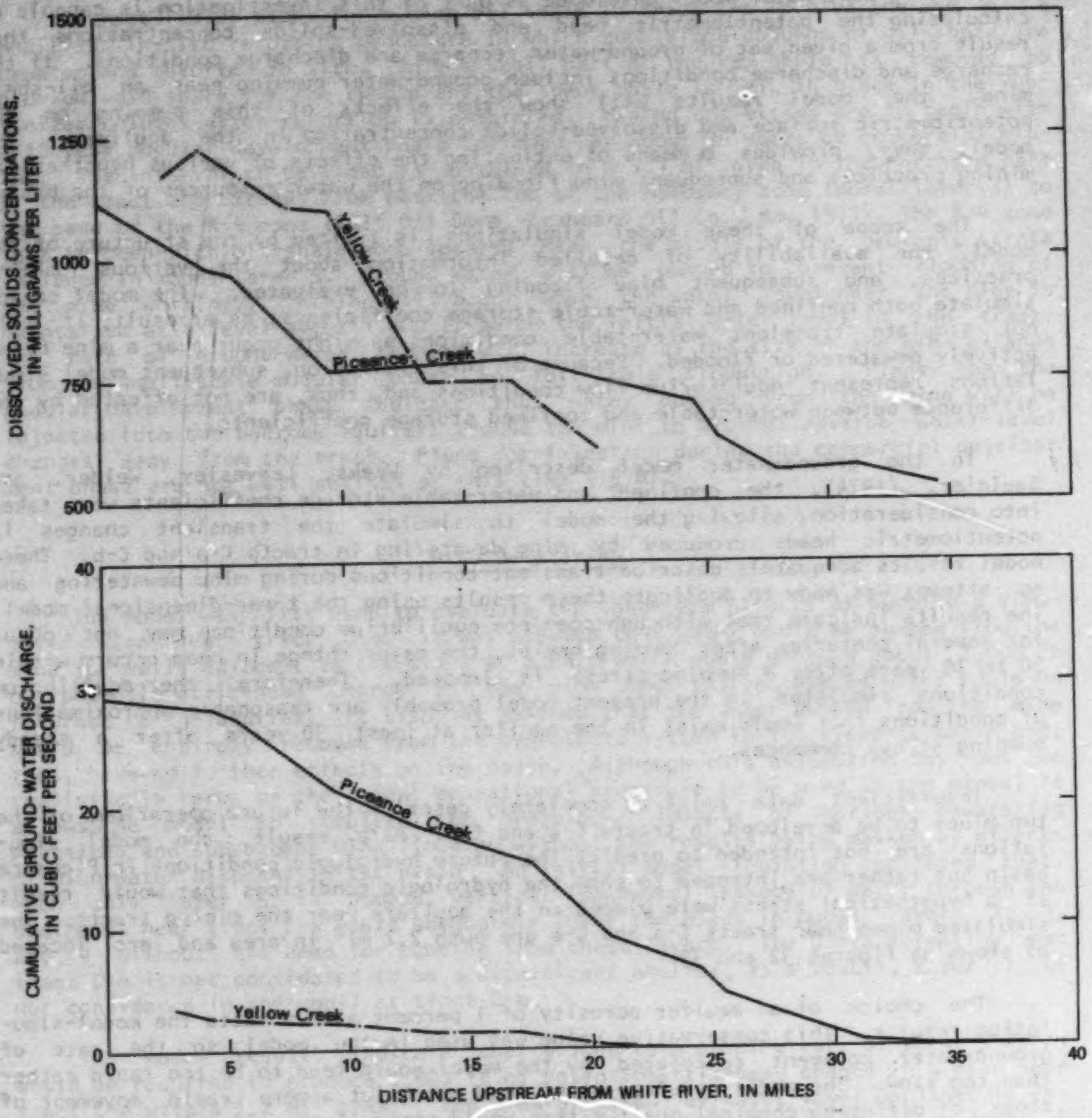


Figure 31.--Cumulative ground-water discharge distribution and dissolved-solids concentrations along Piceance and Yellow Creeks.

MODEL SIMULATIONS

The ground-water model developed as part of this investigation is capable of calculating the potentiometric head and dissolved-solids concentrations that result from a given set of ground-water recharge and discharge conditions. If the recharge and discharge conditions include ground-water pumping near an oil-shale mine, the model results will show the effects of this pumping on the potentiometric surface and dissolved-solids concentration in the aquifers. The model, thus, provides a means of estimating the effects of various hypothetical mining practices and subsequent mine flooding on the water resources of the basin.

The scope of these model simulations is limited by the structure of the model, the availability of detailed information about the various mining practices, and subsequent mine flooding to be evaluated. The model cannot simulate both confined and water-table storage coefficients; as a result, it will not simulate transient water-table conditions as might occur near a mine being actively dewatered or flooded. Because of this limitation, subsequent model simulations represent equilibrium flow conditions and, thus, are not affected by the difference between water-table and confined storage coefficients.

In the ground-water model described by Weeks, Leavesley, Welder, and Saulnier, (1974), the confined and water-table storage coefficients were taken into consideration, allowing the model to simulate the transient changes in potentiometric heads produced by mine dewatering in tracts C-a and C-b. These model results adequately describe transient conditions during mine dewatering and no attempt was made to duplicate these results using the three-dimensional model. The results indicate that although complete equilibrium conditions may not occur for several centuries after pumping begins, the major change in head occurs within 20 to 30 years after a pumping stress is imposed. Therefore, the equilibrium conditions simulated in the present model probably are reasonable approximations of conditions that would exist in the aquifer at least 30 years after a steady pumping stress commences.

Insufficient data exist to completely describe the future operations of the two mines to be developed in tracts C-a and C-b. As a result, the model simulations are not intended to predict the future hydrologic conditions in Piceance basin but rather are intended to show the hydrologic conditions that would result if a hypothetical stress were placed on the aquifers near the mining tracts. The simulated mines near tracts C-a and C-b are both 2.2 mi^2 in area and are located as shown on figures 32 and 39.

The choice of an aquifer porosity of 1 percent also affects the model-simulation results. This conservative value was used in the model so the rate of ground-water movement calculated by the model would tend to be too rapid rather than too slow. The model results, thus, tend to depict a more rapid movement of zones of differing chemical quality than would occur if the effective porosity of the aquifer is larger than 1 percent. In this respect, the model will simulate conditions closer to a "worst case" situation rather than a "best case" situation of contaminant movement.

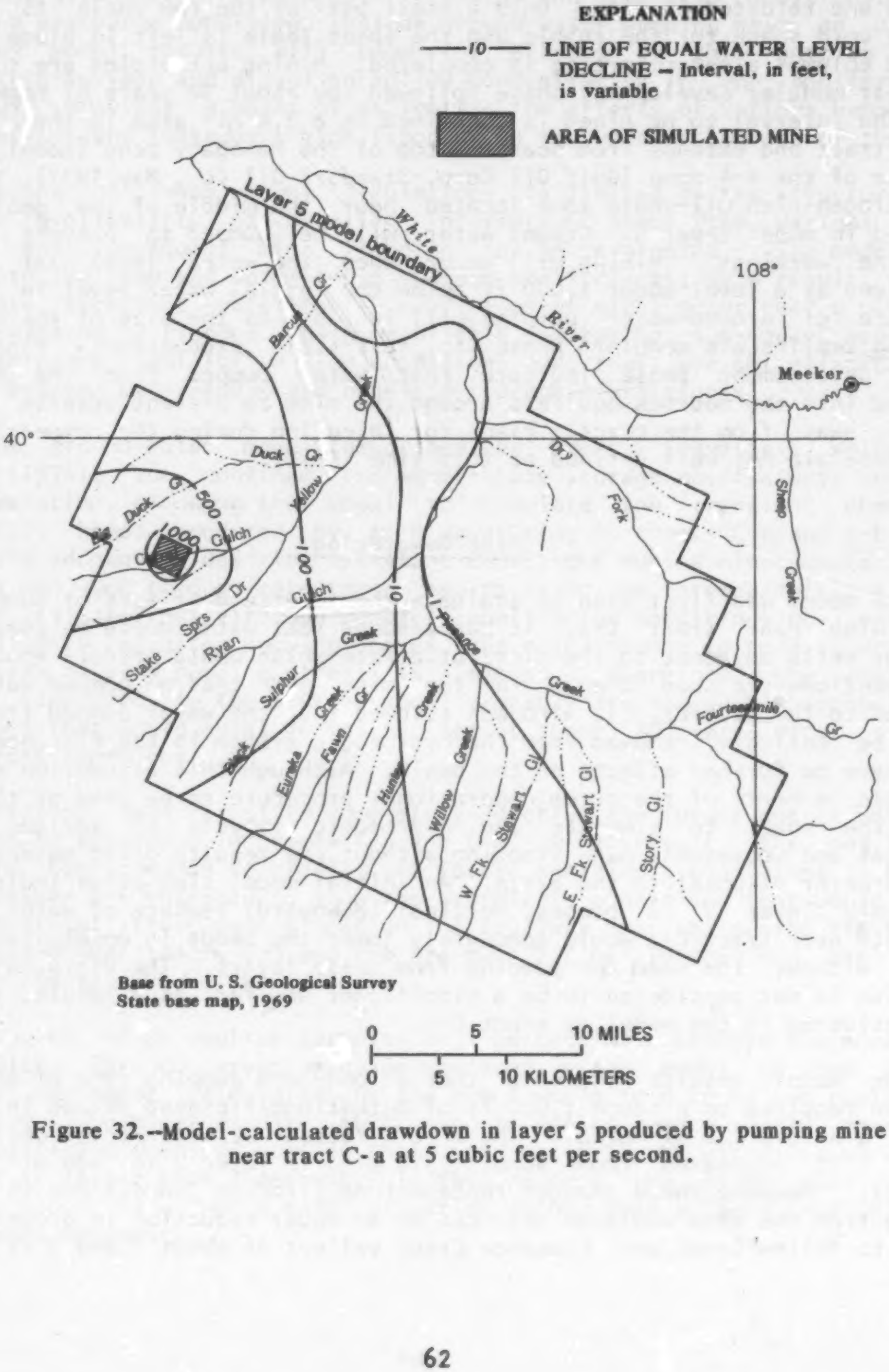
Tract C-a

Current (1978) plans for mining oil shale in tract C-a involve the use of a modified in-situ retorting procedure in which rubbleized columns of oil shale are created and retorted in situ. Only a small part of the raw shale is removed to provide void space for the rubble and the spent shale is left in place in the rubbleized columns after retorting is completed. Mining activities are to begin with a 10-year modular development phase followed by about 30 years of commercial mining. The interval to be mined is contained in a 3.4 mi^2 area in the northern part of the tract and extends from near the top of the Mahogany zone (model layer 3) to the base of the R-4 zone (Gulf Oil Corp.-Standard Oil Co., May 1977). The R-4 zone is a kerogen-rich oil-shale zone located near the middle of the geologic strata included in model layer 5. Ground water will be pumped to prevent flooding of the mine workings. Mining will occur when the water level near the mine is maintained at a level about 1,000 ft below the initial water level in the tract. The rate of ground-water pumping will increase as the size of the mine expands from the small-scale modular phase to full-scale production. Plans for the modular-development phase indicate that water pumped from the mine will be injected into the bedrock aquifers around the mine to prevent adverse water-level changes away from the tract. Plans for injection during the commercial development phase are not well defined at this time (1978).

Mine Dewatering

The model was first used to evaluate the long-term effects of pumping a simulated mine near tract C-a. It was assumed that water would be pumped from the mine (or wells adjacent to the mine) at a rate which would produce about 1,000 ft of potentiometric-head change in the mine and that no pumped water would be returned to the aquifer. It also was assumed that the water pumped from the mine would be entirely removed from the hydrologic system in the Piceance basin and, thus, have no further effects on the basin. Although this assumption may not be realistic in terms of the actual operational procedure to be used at the mines, it allows the model to simulate the hydrologic impacts of various dewatering practices and subsequent mine flooding without the results being masked by effects of mine-water disposal in the basin. An initial model simulation indicated that, when only layer 5 is pumped, vertical (downward) leakage of water through the sediments near tract C-a would adequately lower the heads in model layers 2, 3, and 4 without the need for pumping from these layers. The Uinta Formation near tract C-a is not considered to be a significant aquifer; as a result, layer 1 is not considered in the model at tract C-a.

The model results indicate that a long-term pumping rate of about 5 ft^3/s would be required to produce 1,000 ft of potentiometric-head change in a mine near tract C-a with a 2.2 mi^2 area. The area affected by water-level declines in excess of 1 ft increases from about 370 mi^2 in layer 2 to 480 mi^2 in layer 5 (fig. 32). Because these changes represent equilibrium conditions in the rate of pumping from the mine would be balanced by an equal reduction in ground-water discharge to Yellow Creek and Piceance Creek valleys of about 2 and 3 ft^3/s, respectively.


EXPLANATION
10
LINE OF EQUAL WATER LEVEL DECLINE – Interval, in feet, is variable
AREA OF SIMULATED MINE
Layer 5 model boundary
White
River
108°
Meeker
40°
Barcus
Cr
Duck
Cr
Willow
Big
Duck
Gulch
500
1000
100
10
Stake
Sprs
Dr
Ryan
Gulch
Greek
Piceance
Creek
Dry
Fork
Sheep
Creek
Fourteenmile
Gr
Black
Sulphur
Eureka
Creek
Fawn
Cr
Hunter
Creek
Willow
Creek
W. Fk.
Stewart
Gl
E. Fk.
Stewart
Gl
Story
Gl
0
5
10 MILES
0
5
10 KILOMETERS

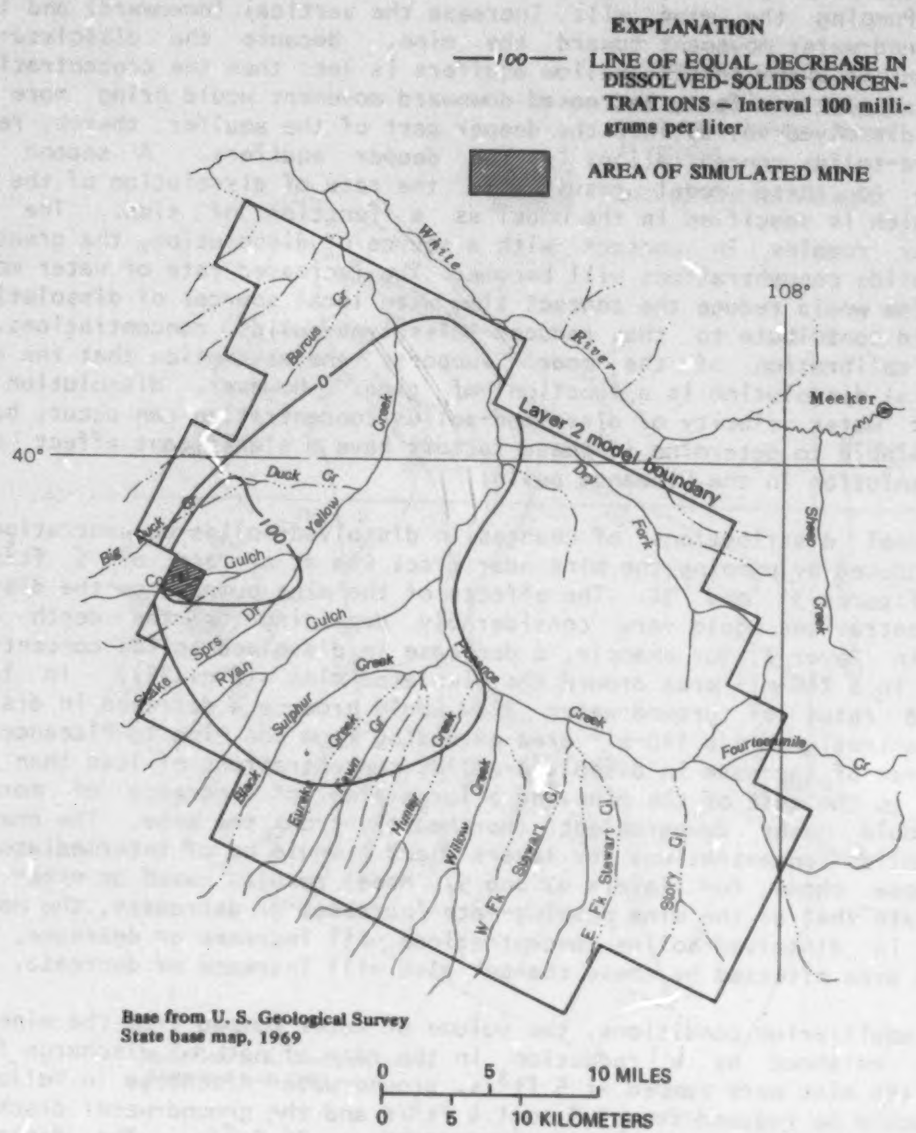
Base from U. S. Geological Survey
State base map, 1969

Figure 32.--Model-calculated drawdown in layer 5 produced by pumping mine near tract C-a at 5 cubic feet per second.

Simulations of various mine-pumping rates indicate that (1) pumping the mine will decrease dissolved-solids concentrations in the water near the mine, and (2) the greater the pumping rate the greater the decrease in dissolved-solids concentrations. Pumping the mine will increase the vertical (downward) and lateral rates of ground-water movement toward the mine. Because the dissolved-solids concentrations in water in the shallow aquifers is less than the concentrations in water in the deeper aquifers, increased downward movement would bring more water with fewer dissolved solids into the deeper part of the aquifer, thereby reducing the dissolved-solids concentrations in the deeper aquifers. A second factor contributing to these model results is the rate of dissolution of the saline minerals, which is specified in the model as a function of time. The longer ground water remains in contact with a source of dissolution, the greater the dissolved-solids concentrations will become. The increased rate of water movement near the mine would reduce the contact time with local sources of dissolution and thereby would contribute to the reduced dissolved-solids concentrations. The successful calibration of the model supports the assumption that the rate of saline-mineral dissolution is a function of time. However, dissolution as a function of water velocity or dissolved-solids concentration can occur, but data are not available to determine if these factors have a significant effect on the rate of dissolution in the Piceance basin.

The areal distributions of changes in dissolved-solids concentrations that would be produced by pumping the mine near tract C-a at a rate of 5 ft^3/s are shown on figures 33 and 34. The effects of the mine pumpage on the dissolved-solids concentrations would vary considerably depending on the depth of the aquifer. In layer 2, for example, a decrease in dissolved-solids concentrations would occur in a 240-mi^2 area around the simulated mine (fig. 33). In layer 5, the altered rates of ground-water flow would produce a decrease in dissolved-solids concentrations in a 140-mi^2 area extending from the mine to Piceance Creek. A small area of increase in dissolved-solids concentrations of less than 50 mg/L would occur to the east of the mine and a large area of increase of more than 400 mg/L would occur downgradient (northeast) from the mine. The changes in dissolved-solids concentrations for layers 3 and 4 would be of intermediate values between those shown for layers 2 and 5. Model results based on other pumping rates indicate that as the mine pumping-rate increases or decreases, the magnitude of change in dissolved-solids concentrations will increase or decrease, and the size of the area affected by these changes also will increase or decrease.

Under equilibrium conditions, the volume of water pumped from the mine would be exactly balanced by a reduction in the rate of natural discharge from the basin. If the mine were pumped at 5 ft^3/s, ground-water discharge in Yellow Creek drainage would be reduced from 3.5 to 1.4 ft^3/s and the ground-water discharge in Piceance Creek drainage would be reduced from 29 to 26 ft^3/s. The distribution and chemical quality of cumulative ground-water discharge in Yellow Creek valley before and after the mine is pumped are shown in figure 35. The model does not separate the base flow, underflow, or evapotranspiration components of ground-water discharge. As a result, the surface flow in Yellow Creek is not directly calculated by the model. However, the model-calculated cumulative ground-water discharge figures give an approximation of surface-water flow and chemical quality without taking into consideration the effects of precipitation runoff, evapotranspiration, or ground-water underflow in the valley alluvium.


EXPLANATION
100
LINE OF EQUAL DECREASE IN DISSOLVED-SOLIDS CONCENTRATIONS — Interval 100 milligrams per liter
AREA OF SIMULATED MINE
108°
40°
Meeker
White
River
Layer 2 model boundary
Barcus
Cr
Creek
0
Duck
Cr
Yellow
100
Big
Duck
Cr
Gulch
Corral
Dry
Fork
Sheep
Creek
Dr
Gulch
Spring
Sprs
Ryan
Creek
Piceance
Creek
Fourteenmile
Cr
Sulphur
Cr
Creek
Black
Sulphur
Eureka
Fawn
Creek
Hunter
Creek
Willow
Creek
W Fk
Stewart
Gl
E Fk
Stewart
Gl
Story
Gl
Stake
0
5
10 MILES
0
5
10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 33.--Model-calculated decrease in dissolved-solids concentrations in layer 2 produced by pumping mine near tract C-a at 5 cubic feet per second.

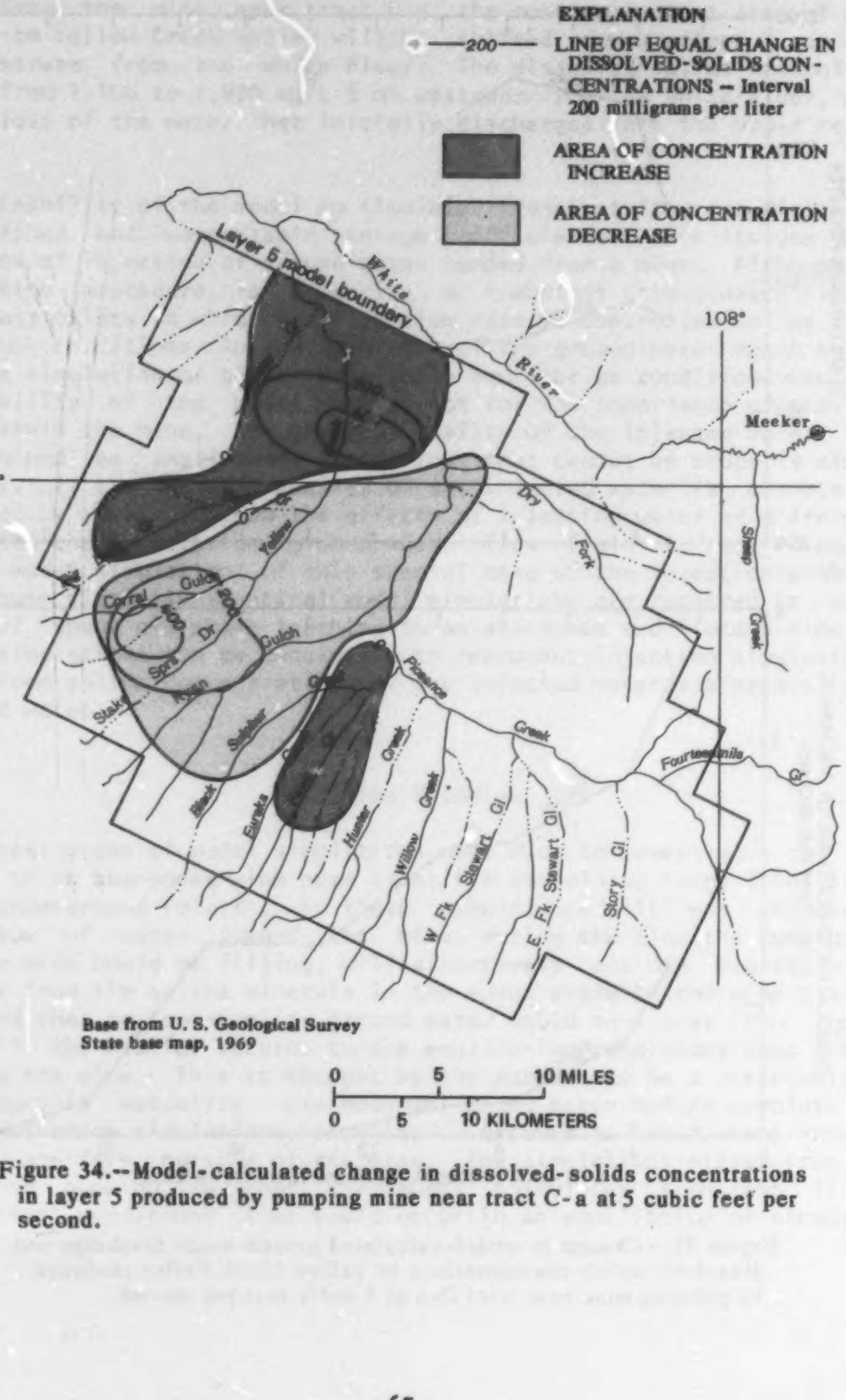

EXPLANATION
—200— LINE OF EQUAL CHANGE IN DISSOLVED-SOLIDS CONCENTRATIONS – Interval 200 milligrams per liter
AREA OF CONCENTRATION INCREASE
AREA OF CONCENTRATION DECREASE
Layer 5 model boundary
White River
108°
40°
Meeker
Dry Fork
Sheep Creek
Yellow Cr.
Corral Gulch
Spring Dr.
Ryan Gulch
Stake
Piceance Creek
Black
Sulphur
Eureka
Hunter
Willow Creek
W. Fk. Stewart Gl.
E. Fk. Stewart Gl.
Story Gl.
Fourteenmile Gr.
200
400
0
Base from U. S. Geological Survey State base map, 1969
0 5 10 MILES
0 5 10 KILOMETERS

Figure 34.--Model-calculated change in dissolved-solids concentrations in layer 5 produced by pumping mine near tract C-a at 5 cubic feet per second.

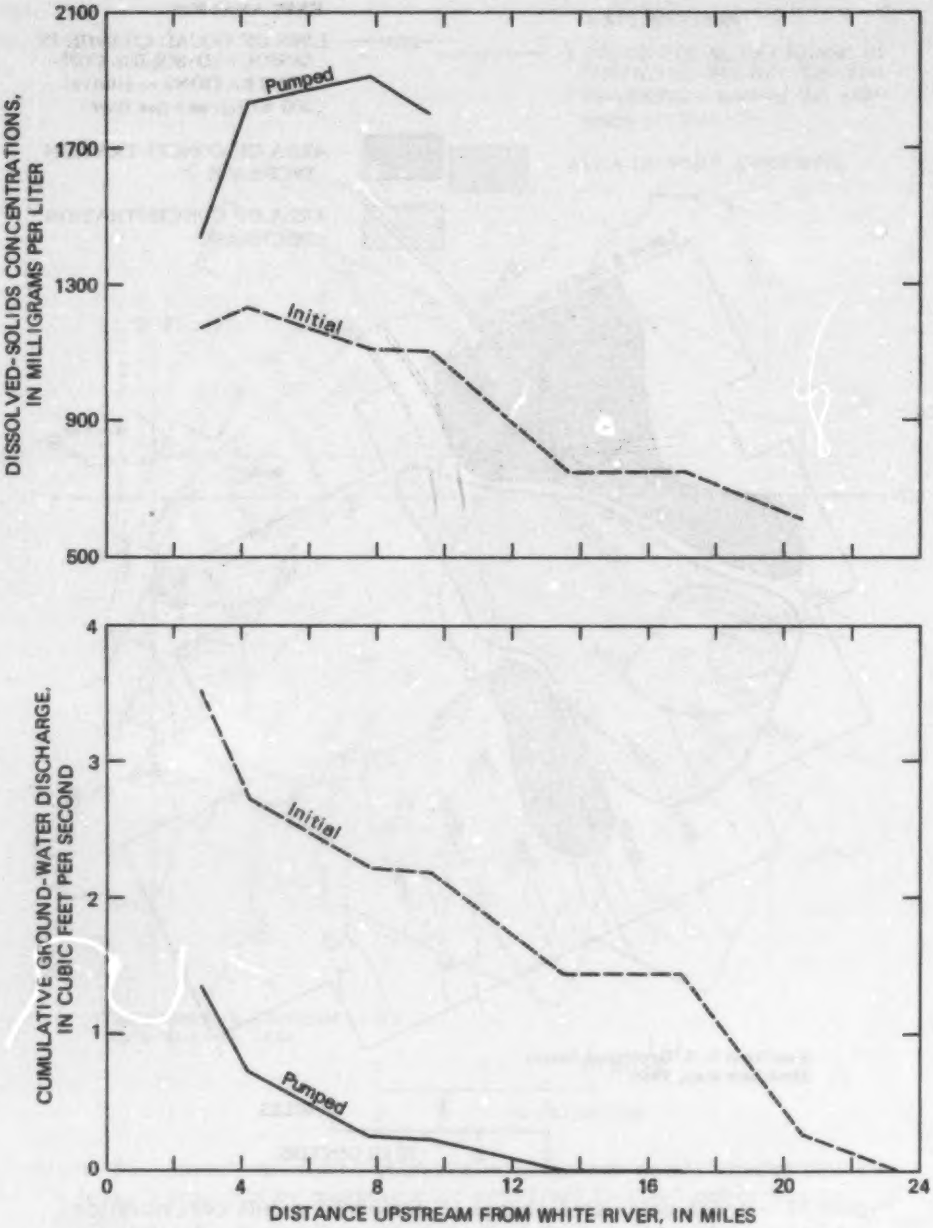


Figure 35.--Change in model-calculated ground-water discharge and dissolved-solids concentrations in Yellow Creek Valley produced by pumping mine near tract C-a at 5 cubic feet per second.

The most upgradient area of ground-water discharge to Yellow Creek valley occurs 20 to 23 mi upstream from the confluence with the White River under the initial or present-day conditions. After the basin reaches equilibrium with the pumping from the mine near tract C-a, the most upgradient area of ground-water discharge to Yellow Creek valley will be shifted downgradient, occurring 9 to 13 mi upstream from the White River. The dissolved-solids concentrations will increase from 1,100 to 1,900 mg/L 8 mi upstream from the White River, as a result of the loss of the water that initially discharged into the upper reaches of the valley.

The inability of the model to simulate transient-flow conditions involving both confined and water-table storage coefficients limits its use in evaluating the effects of injection of ground water pumped from a mine. Although the pumping-injection procedure is primarily a transient ground-water flow problem, a special case exists in which the injection rate is controlled so as to maintain equilibrium conditions in the remainder of the ground-water basin outside of the mine. The simulation of these large-scale equilibrium conditions would be within the capability of the model were it not for the importance of small-scale conditions within the mine. The chemical quality of the injected water, for example, is determined by small-scale conditions that cannot be properly simulated with this model. If the chemical quality of the injected water is predetermined, the model can be used to show the effects of injecting water of different chemical quality into the equilibrium ground-water flow field in the Piceance basin. Separate model simulations of this special case of the injection problem were not made, because virtually identical model simulations are required to simulate the effects of spent oil-shale leaching in an abandoned and flooded mine. The mine-leaching simulations can be considered to represent injection simulations in which the dissolved-solids concentrations of the injected water are greater than that of the ground water.

Mine Flooding

The next group of model simulations were made to investigate the effects of flooding of an abandoned mine near tract C-a containing large quantities of spent shale in underground retorts. In these simulations, it was assumed that the radial flow of water toward the mine, during the time the cone of depression around the mine would be filling, will effectively halt any migration of ground water away from the saline minerals in the spent shale in the mine. In effect, it was assumed that no poor-quality ground water would move away from the abandoned mine until the aquifer returns to the equilibrium conditions that occurred prior to pumping the mine. This is thought by the authors to be a reasonable assumption even though in actuality some movement might occur before complete equilibrium exists. For these simulations, leaching is assumed to begin when leachate moves into the aquifers outside of the mine. The simulations differ from those simulating mine pumping in that the model calculates transient (time-varying) concentration conditions that would occur in an equilibrium or steady-state flow system.

As mentioned previously, spent oil shale may contain soluble saline minerals in concentrations ranging from 1 to 5 percent by weight. The rate of dissolution of these minerals by ground water will be affected by indeterminate factors, such as retorting temperatures, shale particle size, and permeability of the retorts. Management of the oil-shale mines during and after the retorting operations can drastically affect these factors and, thus, the rate of dissolution that will occur in the abandoned and flooded mine.

The model was used to determine the effects of various mine-leaching rates since the actual rate to be expected is not known. The change in dissolved-solids concentrations after 60 years of leaching, shown in figure 36, is calculated from initial conditions in the basin aquifers prior to the effects of mine pumping. As shown, the mine leachate would have the most pronounced effect on the water quality in the layer with the largest hydraulic conductivity (layer 2) and the least effect in the layer with the smallest hydraulic conductivity (layer 3). Dissolved-solids concentrations as much as 50,000 mg/L would occur in layer 2 adjacent to the mine after 60 years of leaching at rates that are thought to be possible for an actual mine in tract C-a.

The longer the mine leaching continues, the more pronounced the water-quality changes in the aquifer will become. The change in dissolved-solids concentrations in each model layer for 60 years of constant mine leaching at a rate of 1.3×10^5 lb/d is shown in figure 37. The large volume of water initially in and near the simulated mine containing relatively small concentrations of dissolved solids would mix with the influx of mine leachate to produce the gradual change in water quality shown. Throughout the 60-year simulation period, the layers with the largest hydraulic conductivity show the largest change in concentration.

The areal distribution of the water-quality change in layer 2 is shown on figure 38. Dissolved-solids concentrations will increase by more than 1,000 mg/L in a 30-mi^2 area downgradient from the mine after 60 years of mine leaching. Dissolved-solids increases in excess of 10 mg/L will occur in a 140-mi^2 area. As indicated by the changes shown in figure 37, the areas affected by water-quality changes in the other model layers would be smaller than the areas in layer 2. Only minor changes in water quality in Yellow Creek will result after 60 years of leaching, primarily because water with relatively large dissolved-solids concentrations will not have reached the main areas of ground-water discharge along the creek.

If the mine is managed so as to minimize the rate of dissolution of the saline minerals in the abandoned retorts, the effects on the ground-water quality could be much less significant than those shown by these model simulations. Conversely, disregard for spent-shale leaching problems could lead to a serious and long-term degradation in the ground-water quality in Piceance basin.

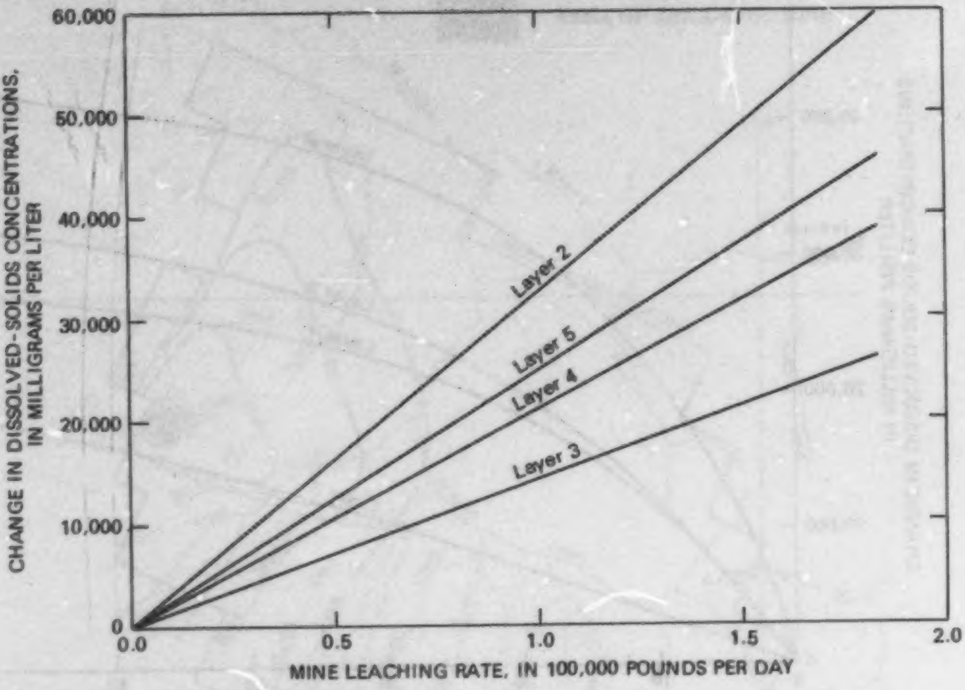


Figure 36.—Change in dissolved-solids concentrations in aquifers adjacent to abandoned mine near tract C-a after 60 years of leaching.

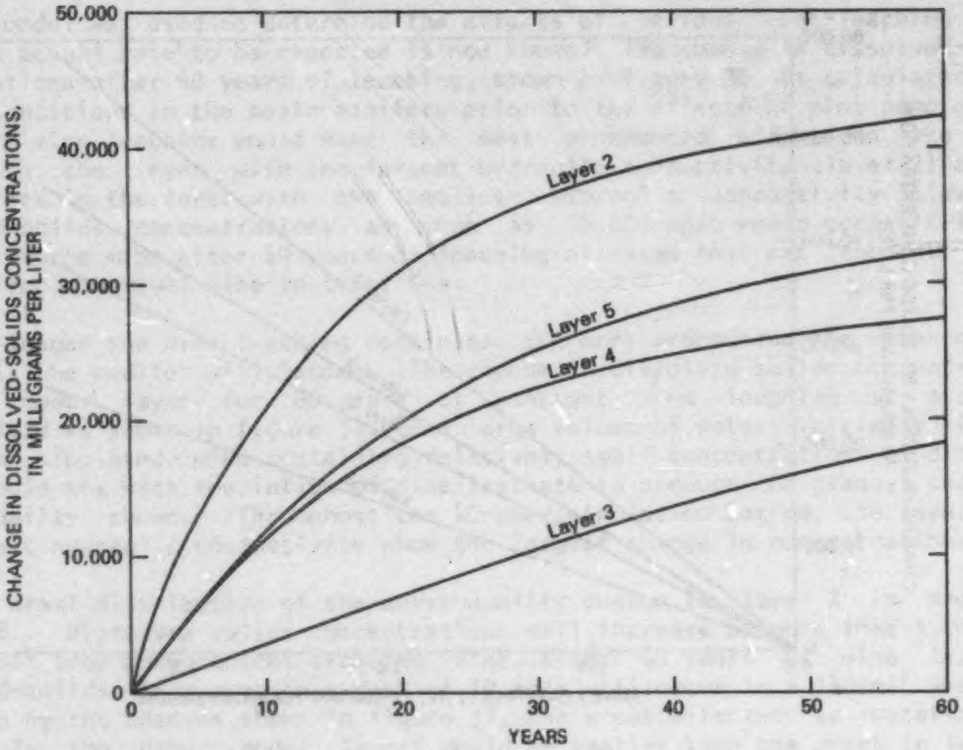
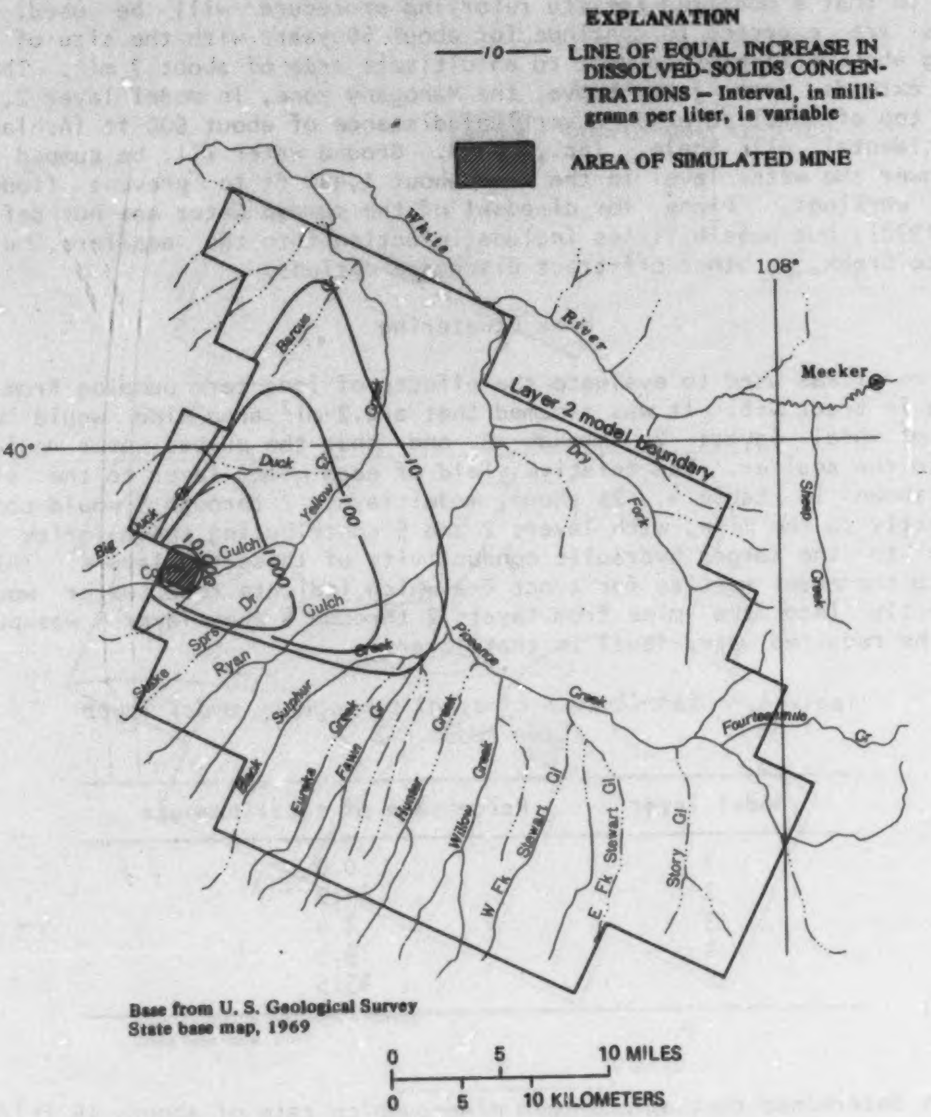


Figure 37.--Change in dissolved-solids concentrations with time in aquifers adjacent to abandoned mine for leaching rate of 1.3 x 10^5 pounds per day.


EXPLANATION
—10— LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
AREA OF SIMULATED MINE
White
River
108°
Meeker
40°
Layer 2 model boundary
Dry
Fork
Sheep
Creek
Piceance
Creek
Fourteenmile
Cr
Barcus
Duck
Cr
Yellow
Big
Jack
Gulch
Cr
Dr
Gulch
Creek
Sprs
Ryan
Stake
Sulphur
Black
Eureka
Creek
Cr
Fawn
Cr
Hunter
Creek
Willow
Creek
Cr
W. Fk.
Stewart
Cr
E. Fk.
Stewart
Cr
Story
Cr
10
100
1000
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 38.--Model-calculated increase in dissolved-solids concentrations in layer 2 after 60 years of leaching from abandoned mine at 1.3 x 10^5 pounds per day.

Tract C-b

Plans for mining oil shale in tract C-b are similar to the planned mining in tract C-a in that a modified in-situ retorting procedure will be used. Mining operations are expected to continue for about 60 years with the size of the mine increasing about 0.12 mi^2 per year to an ultimate area of about 7 mi^2. The mining interval extends from just above the Mahogany zone, in model layer 2, to just below the top of model layer 5, a vertical distance of about 500 ft (Ashland Oil, Inc., Occidental Oil Shale, Inc., 1977). Ground water will be pumped from the mine to lower the water level in the mine about 1,400 ft to prevent flooding of the mine workings. Plans for disposal of the pumped water are not definite at present (1978), but possibilities include injection into the aquifers, discharge to Piceance Creek, or other off-tract discharge options.

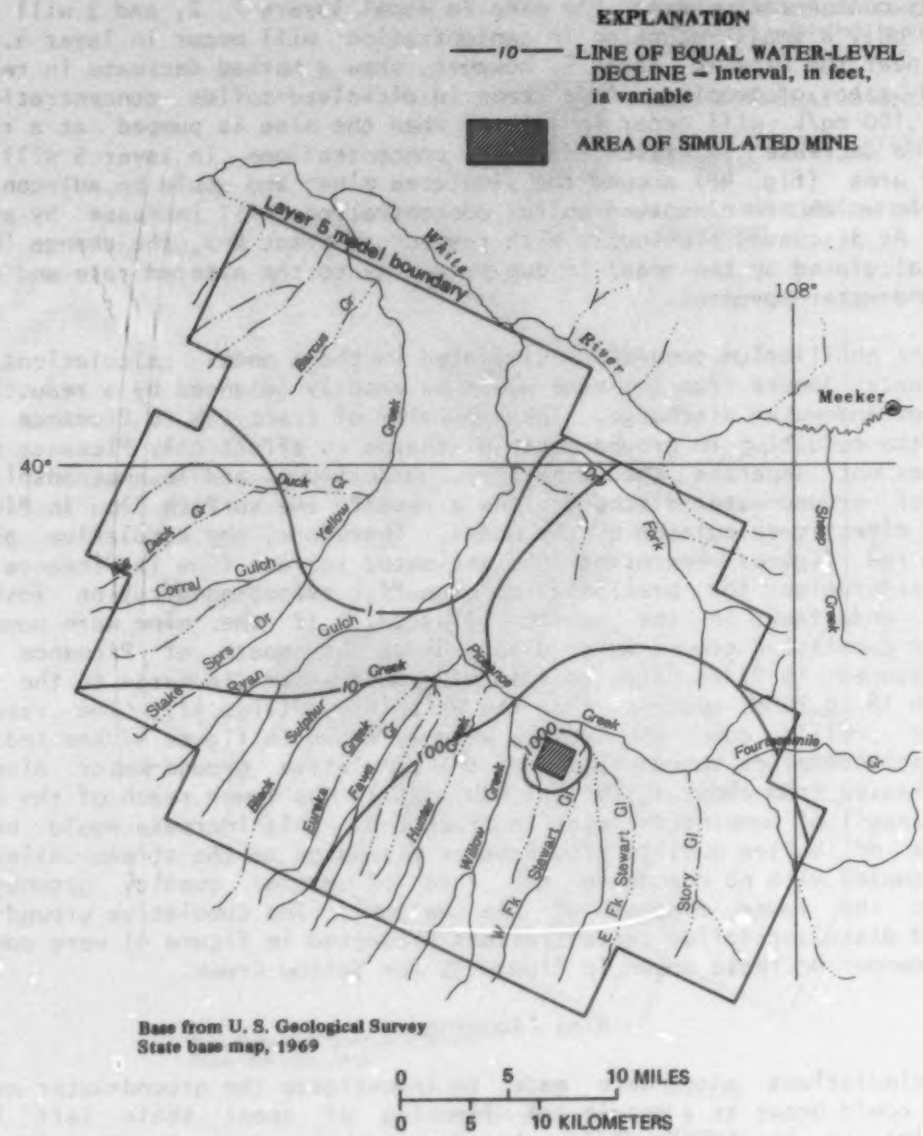
Mine Dewatering

The model was used to evaluate the effects of long-term pumping from a simulated mine in tract C-b. It was assumed that a 2.2-mi^2 area mine would withdraw water from model layers 2 through 5 and that the pumped water would not be returned to the aquifer. The relative yield of each model layer to the simulated mine is shown in table 4. As shown, model layers 2 through 5 would contribute water directly to the mine, with layers 2 and 5 contributing the majority of the water due to the larger hydraulic conductivity of these two layers. This is in contrast to the model results for tract C-a which indicate that water would not flow directly into the mine from layers 2 through 4 when layer 5 was pumped to maintain the required water level in that layer.

Table 4.--*Distribution of total pumpage by model layer for tract C-b*

Model layer	Percentage of total pumpage
1	0.0
2	41.2
3	3.4
4	9.9
5	45.5

It was determined that a long-term mine-pumping rate of about 15 ft^3/s will be needed to maintain the required 1,400-ft water-level decline in layer 5 in tract C-b. The distribution of pumping shown in table 4 produced about 800, 900, 1,100, 1,200, and 1,400 ft of water-level decline in tract C-b in model layers 1 through 5, respectively. Water-level declines in layer 5 in excess of 1 ft will occur in a 560-mi^2 area of the Piceance basin with declines in excess of 100 ft occurring in a 240-mi^2 area in the southern part of the basin (fig. 39). Progressively smaller areas of equal water-level decline will occur in the layers above layer 5. In layer 1, for example, declines in excess of 1 ft will occur in a 410-mi^2 area.


EXPLANATION
10 LINE OF EQUAL WATER-LEVEL DECLINE – Interval, in feet, is variable
▨ AREA OF SIMULATED MINE
Layer 5 model boundary
White River
108°
40°
Meeker
Barcus Cr
Creek
Duck Cr
Yellow
Corral Gulch
Sprs Dr
Gulch
Stake
Ryan
10 Creek
Sulphur
Black
Eureka Creek
Fawn Cr
Hunter
100
1000
Piceance
Willow Creek
W. Fk Stewart Gl
Stewart Gl
E. Fk Stewart Gl
Story Gl
Fork
Sheep Creek
Fourmile Gr
Creek
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey State base map, 1969

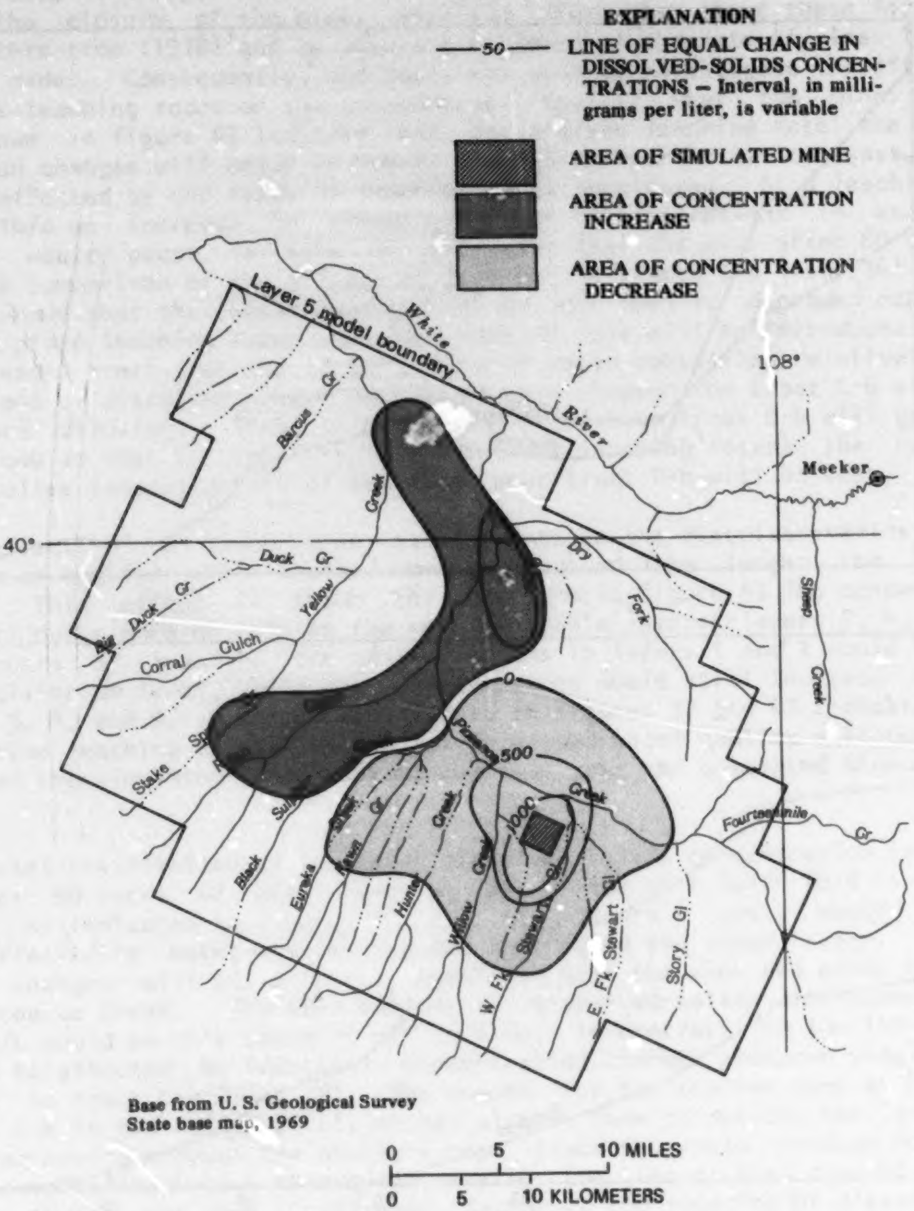
Figure 39.--Model-calculated drawdown in layer 5 produced by pumping mine in tract C-b at 15 cubic feet per second.

Simulations were made using different mine-pumping rates to show the long-term effects of the pumping on the water quality in the aquifers. Results of these simulations indicate that, as the mine-pumping rate increases, the dissolved-solids concentration near the mine in model layers 1, 2, and 3 will remain constant and only a small reduction in concentration will occur in layer 4. Concentrations near the mine in layer 5, however, show a marked decrease in response to increased rates of pumping. A decrease in dissolved-solids concentrations of as much as 1,100 mg/L will occur in layer 5 when the mine is pumped at a rate of 15 ft^3/s. The decrease in dissolved-solids concentrations in layer 5 will occur in a 120-mi^2 area (fig. 40) around the simulated mine and would be adjacent to a 90-mi^2 area in which the dissolved-solids concentration will increase by as much as 50 mg/L. As discussed previously with respect to tract C-a, the change in concentration calculated by the model is due primarily to the altered rate and direction of ground-water movement.

Under the equilibrium conditions simulated in these model calculations, the volume of water pumped from the mine would be exactly balanced by a reduction in the rate of ground-water discharge. The proximity of tract C-b to Piceance Creek will cause the reduction in ground-water discharge to affect only Piceance Creek. The model does not separate the base-flow, underflow, and evapotranspiration components of ground-water discharge. As a result, the surface flow in Piceance Creek is not directly calculated by the model. Therefore, the cumulative ground-water discharge figures represent the estimated surface flow in Piceance Creek without consideration for precipitation runoff, evapotranspiration loss, or ground-water underflow in the valley alluvium. If the mine were pumped at 15 ft^3/s, the cumulative ground-water discharge at the mouth of Piceance Creek would be reduced 15 ft^3/s due to loss of ground-water discharge to the valley along a reach 18 to 30 mi upstream from the White River (fig. 41). The resulting concentration profile down the valley also is shown in figure 41 and indicates that the dissolved-solids concentration of the cumulative ground-water discharge will be increased from about 1,100 to 1,400 mg/L in the lower reach of the stream valley as a result of pumping the mine in tract C-b. This increase would be due to the loss of better quality ground-water discharge to the stream valley near tract C-b, coupled with no change in the rate of poorer quality ground-water discharge to the lower reaches of the valley. The cumulative ground-water discharge and dissolved-solids concentrations presented in figure 41 were computed in the same manner as those shown in figure 35 for Yellow Creek.

Mine Flooding

Model simulations also were made to investigate the ground-water quality changes that could occur as a result of leaching of spent shale left in an abandoned mine in tract C-b. As for tract C-a, these simulations were based on the assumption that insignificant movement of mine leachate would occur prior to the time the water levels around the mine returned to near equilibrium (prepumping) conditions. These model simulations depict transient concentration conditions that would occur in an equilibrium ground-water flow field.


EXPLANATION
50 LINE OF EQUAL CHANGE IN DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
AREA OF SIMULATED MINE
AREA OF CONCENTRATION INCREASE
AREA OF CONCENTRATION DECREASE
Layer 5 model boundary
White River
108°
40°
Meeker
Barcus Cr
Creek
Duck Cr
Duck Cr
Big
Yellow
Corral
Gulch
Stake
Sp
Dry
Fork
Sheep
Creek
0
Piceance
500
Creek
1000
Fourteenmile
Cr
Black
Sulphur
Eureka
Fawn
Gr
Hunter
Creek
Willow
Creek
W. Fk
Stewart
Gl
Stewart
E. Fk
Story
Gl
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 40.--Model-calculated change in dissolved-solids concentrations in layer 5 produced by pumping mine in tract C-b at 15 cubic feet per second.

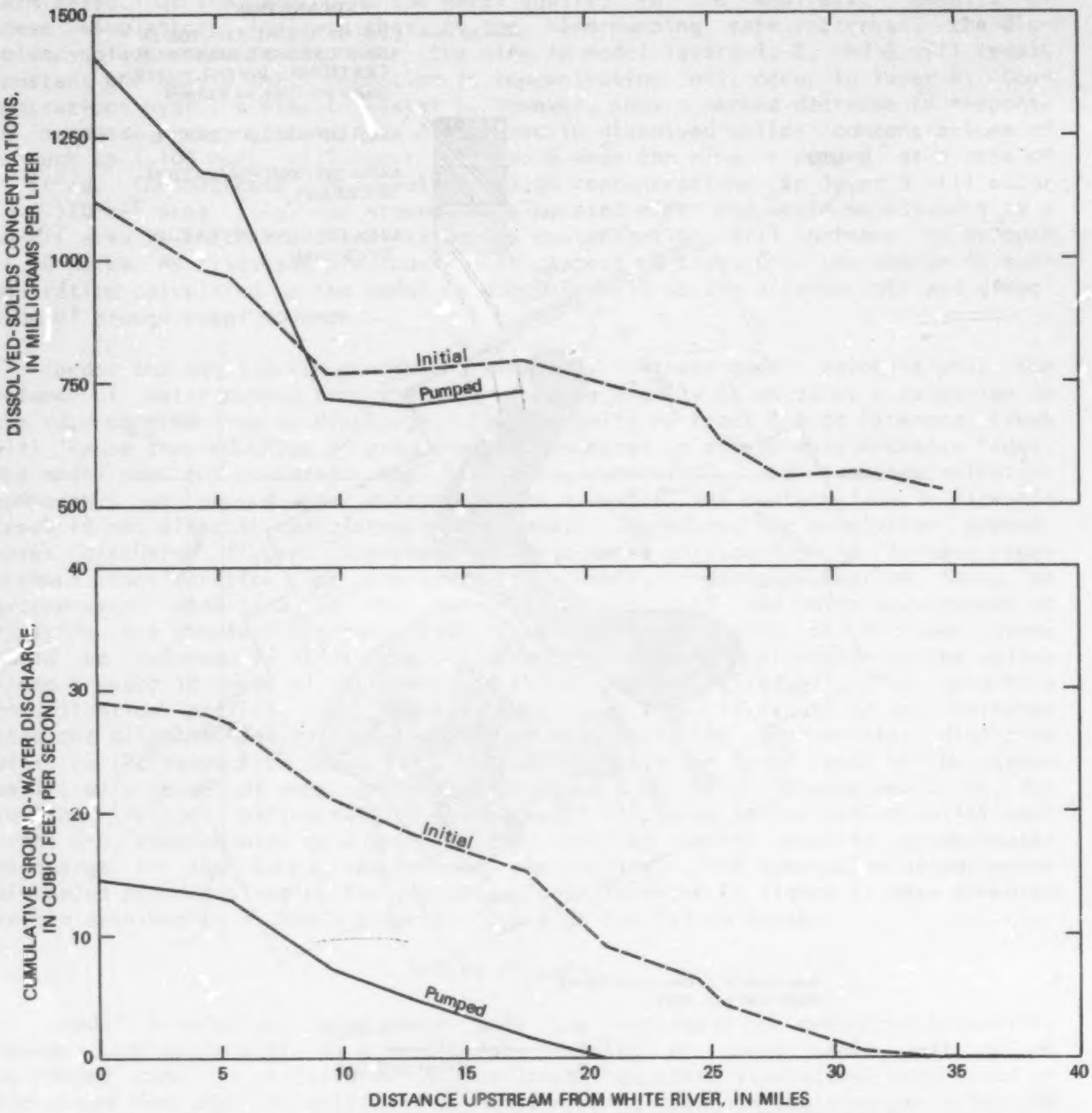


Figure 41.--Change in model-calculated ground-water discharge and dissolved-solids concentrations in Piceance Creek Valley produced by pumping mine in tract C-b at 15 cubic feet per second.

The rate of dissolution of saline minerals in the spent shale in tract C-b will be affected to a major extent by mining practices and subsequent steps taken prior to the closure of the mine. Specific information about these factors is tenuous at this time (1978) and an accurate estimate of the rate of mine leaching cannot be made. Consequently, the model was used to investigate the effects of various mine-leaching rates on the ground-water quality near the mine. Model results shown in figure 42 indicate that, for a given leaching rate, the largest concentration changes will occur in layers 4 and 5. Layer 1, by contrast, would be little affected by the range of leaching rates considered. At a leaching rate of 1.3×10^5 lb/d an increase in dissolved-solids concentrations in excess of 20,000 mg/L would occur in some of the water near the mine after 60 years of leaching. A comparison of the effects of leaching in tracts C-a (fig. 36) and C-b (fig. 42) shows that the water quality will be more readily degraded near tract C-a. For a given leaching rate, the same mass of salt will be introduced to the water in each tract, but the larger volume of water containing relatively small concentrations of dissolved solids that would move through the tract C-b area will produce more dilution. Thus, although the water near tract C-b will carry the same salt load as that in tract C-a (for identical leaching rates), the resultant dissolved-solids concentrations of the water near tract C-b will be less.

The effect of a given mine-leaching rate on the dissolved-solids concentrations in an aquifer will become more pronounced the longer the leaching continues. This effect is shown for tract C-b in figure 43 The concentration changes will occur more quickly in the more permeable layers--layers 2, 4, and 5. After 60 years of leaching, the concentrations in layers 1 and 2 would be at or near an equilibrium level, while the concentrations would still increase steadily in layers 3, 4, and 5. A comparison of data in figures 37 and 43 indicates that, for equal mine leaching rates, the changes in ground-water quality will occur more rapidly near the simulated mine in tract C-a than near the simulated mine in tract C-b.

The areal distribution of increased dissolved-solids concentration in layer 4 and 5 after 60 years of mine leaching at a rate of 1.3×10^5 lb/d is shown in figure 44. As indicated in figures 42 and 43, layers 4 and 5 would be more severely affected by water-quality changes than would the other layers. The concentration changes will be primarily localized near the mine and along the south side of Piceance Creek. The area subject to dissolved-solids increases greater than 10 mg/L would be only about 40 mi^2 in size, in contrast to the 140-mi^2 area that would be affected by identical concentration changes produced under similar conditions in tract C-a (fig. 38). The reason for the smaller zone of influence near tract C-b is two-fold. First, as has already been discussed, the larger volume of water moving through the aquifers near tract C-b would produce more dilution of the mine leachate, thereby decreasing the size of the zone of degraded water. The second and more significant factor is the location of Piceance Creek with respect to tract C-b. Ground water moving near tract C-b is able to travel only a few miles before being discharged to the alluvial aquifer or surface flow in Piceance Creek. As a result, the degraded water near the mine would affect the surrounding ground-water quality in only a limited area before being removed from the aquifer system by the surface drainage.

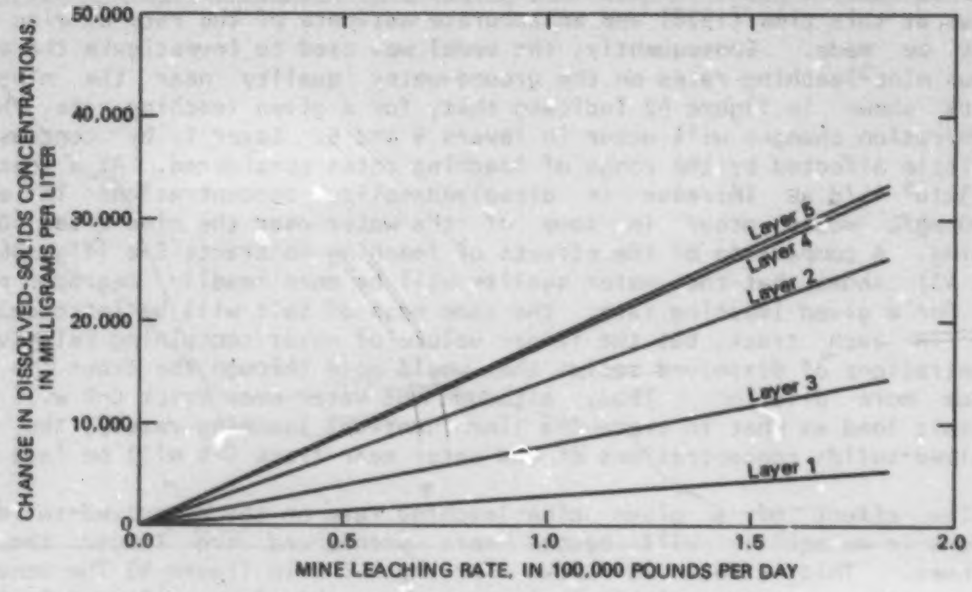


Figure 42.—Change in dissolved-solids concentrations in aquifers adjacent to abandoned mine in tract C-b after 60 years of leaching.

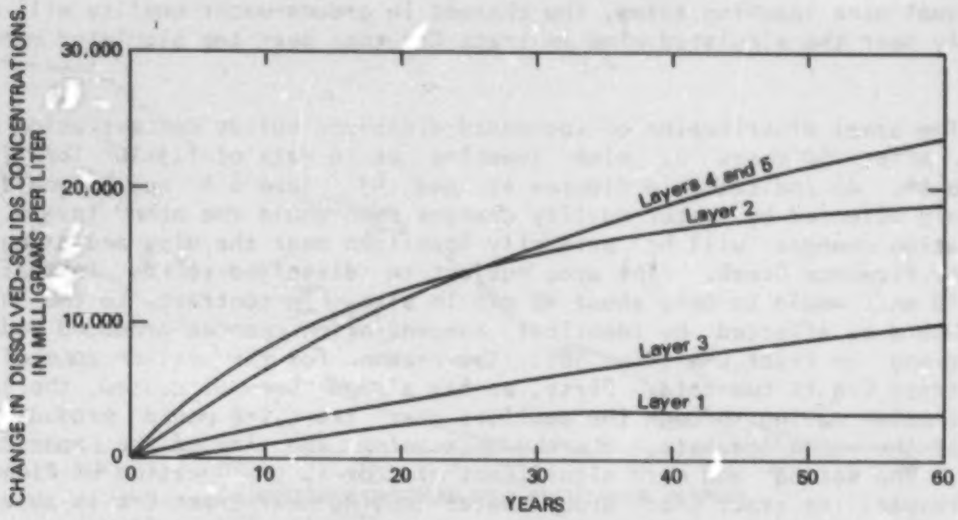
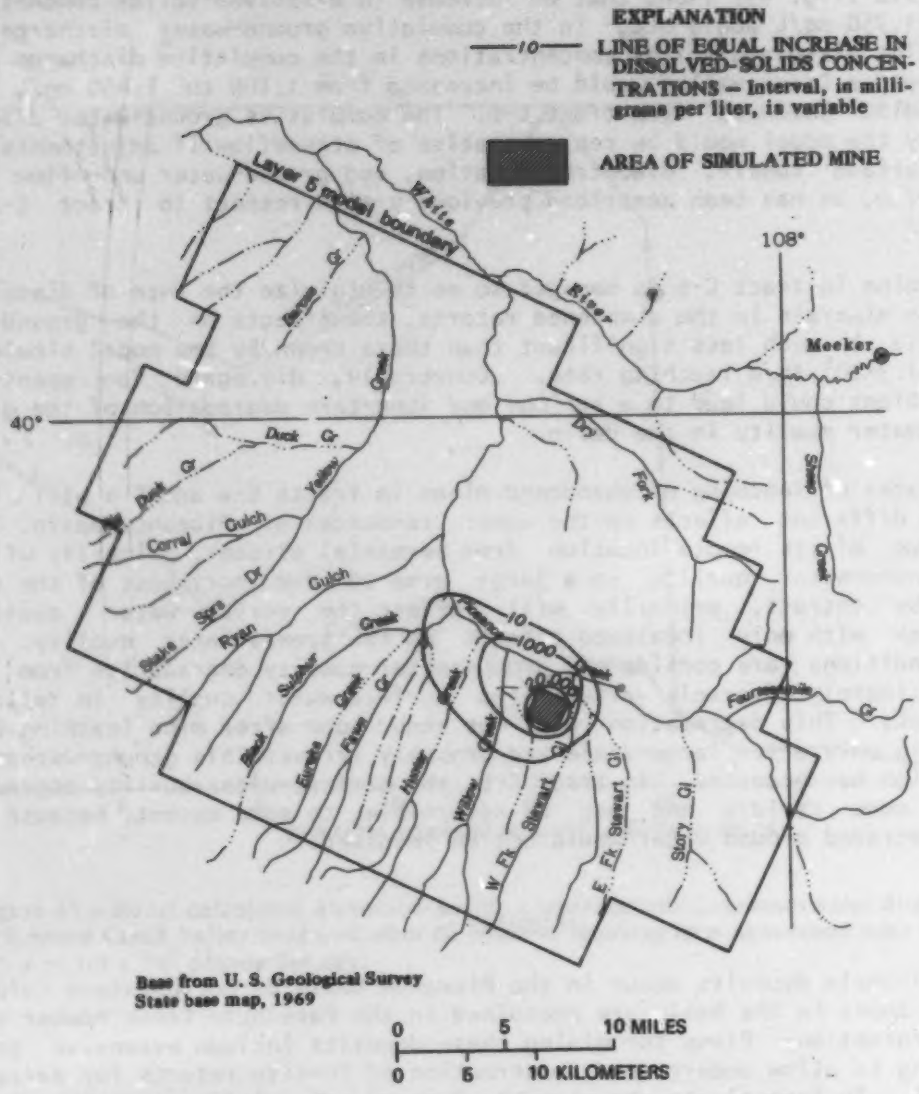


Figure 43.—Change in dissolved-solids concentrations with time in aquifers adjacent to abandoned mine in tract C-b for leaching rate of 1.3 x 10^5 pounds per day.


EXPLANATION
10
LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATIONS – Interval, in milligrams per liter, is variable
AREA OF SIMULATED MINE
Layer 5 model boundary
White
River
108°
Meeker
40°
Duck Cr
Duck Cr
Yellow Creek
Corral Gulch
Ryan Gulch
Spring Cr
Sulphur Creek
Piceance Creek
Fawn Cr
Hunter Cr
Willow Creek
W. Fk. Stewart Gl
E. Fk. Stewart Gl
Story Gl
Fourmile Gr
Dry Fork
Sheep Creek
Black Sulphur
Eureka Creek
Stake Spring
10
1000
10,000
0 5 10 MILES
0 5 10 KILOMETERS

Base from U. S. Geological Survey
State base map, 1969

Figure 44.—Model-calculated increase in dissolved-solids concentrations in layer 5 after 60 years of leaching from abandoned mine at 1.3 x 10^5 pounds per day.

Previous simulations have shown that pumping the mine in tract C-b would have a pronounced effect on the volume of ground-water discharge to Piceance Creek valley. In a like manner, leaching of the mine in tract C-b would have a pronounced effect on the water quality in the valley. The dissolved-solids concentration profile (fig. 45) shows that an increase in dissolved-solids concentration from 750 to 1,750 mg/L would occur in the cumulative ground-water discharge near tract C-b. The dissolved-solids concentrations in the cumulative discharge at the mouth of Piceance Creek valley would be increased from 1,100 to 1,450 mg/L as a result of mine leachate from tract C-b. The cumulative ground-water discharge calculated by the model would be representative of streamflow if adjustments were made for surface runoff, evapotranspiration, and ground-water underflow in the valley alluvium, as has been described previously with respect to tract C-a and Yellow Creek.

If the mine in tract C-b is managed so as to minimize the rate of dissolution of the saline minerals in the abandoned retorts, the effects on the ground-water quality could be much less significant than those shown by the model simulations that used a 1.3×10^5 lb/d leaching rate. Conversely, disregard for spent-shale leaching problems could lead to a serious and long-term degradation of the ground- and surface-water quality in the basin.

Equal rates of leaching of abandoned mines in tracts C-a and C-b will likely produce much different effects on the water resources of Piceance basin. Tract C-a, by virtue of its remote location from perennial streams, primarily will affect the ground-water quality in a large area to the northeast of the tract. Tract C-b, by contrast, primarily will affect the surface-water quality in Piceance Creek with only localized effects on the ground-water quality. When long-term conditions are considered, ground-water-quality degradation from tract C-a will ultimately adversely affect the surface-water quality in Yellow and Piceance Creeks. This degradation will not occur soon after mine leaching begins but will begin only after large-scale and probably irreversible ground-water-quality degradation has occurred. In tract C-b, the surface-water-quality degradation will occur more rapidly and may be reversible, to some extent, because large volumes of degraded ground water would not be involved.

SUMMARY

Rich oil-shale deposits occur in the Piceance basin of northwestern Colorado. The richest zones in the basin are contained in the Parachute Creek Member of the Green River Formation. Plans for mining these deposits include extensive ground-water pumping to allow underground construction of in-situ retorts for extracting the shale oil. To investigate the possible impacts of mining on the chemical quality of the water resources in the basin, a study of the geochemistry of the basin was conducted in conjunction with an evaluation of the planned mining activities using a three-dimensional mathematical model that simulates solute transport in the ground-water system.

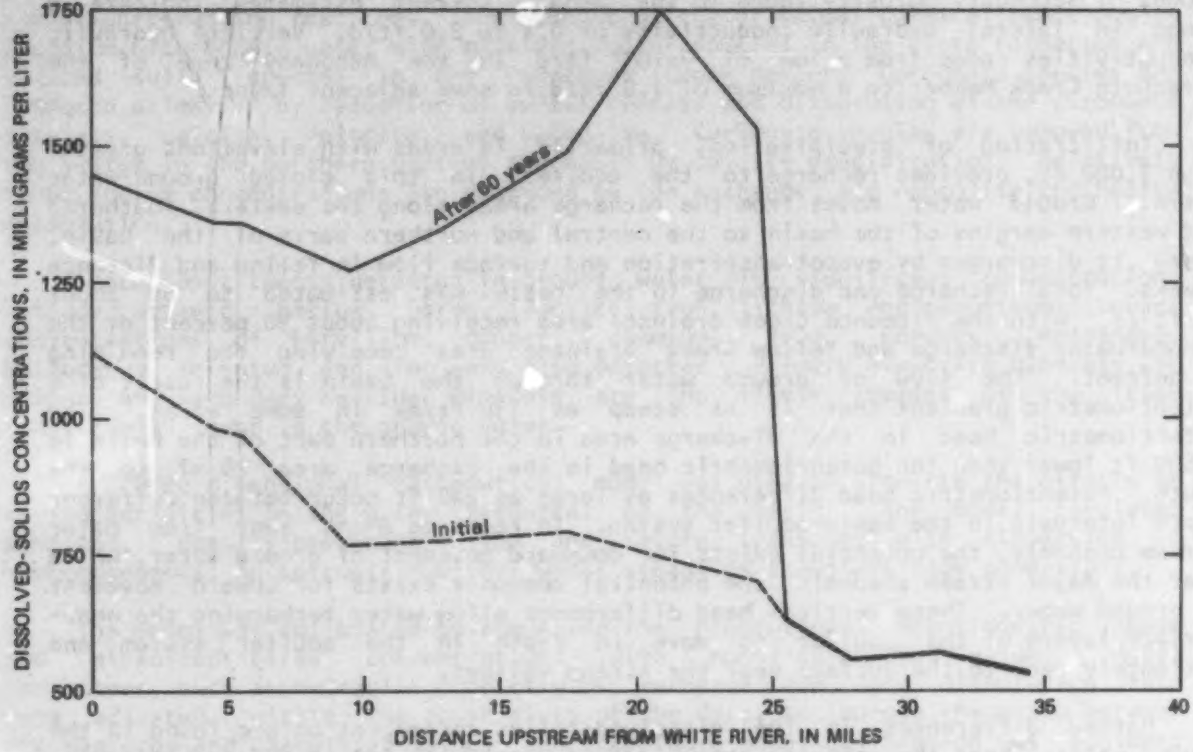


Figure 45.--Model calculated dissolved-solids concentrations in ground-water discharge to Piceance Creek Valley produced after 60 years of leaching from abandoned mine in tract C-a at 1.3 x 10^5 pounds per day.

The principal aquifers in the basin occur in the Uinta Formation, composed of sandstone and siltstone, and in the underlying Parachute Creek Member of the Green River Formation, which consists of dolomitic marlstone. These units are permeable as a result of secondary porosity produced by joints, faults, collapse breccia, and solution cavities. The combined saturated thickness of these units varies from 0 near the outcrops on the eastern, northern, and western margins of the basin to as much as 2,000 ft in the northeastern part of the basin. The hydraulic conductivity of these units varies considerably, depending on differences in the amount of secondary porosity found in the area. Current estimates indicate a range in lateral hydraulic conductivity of 0.1 to 2.0 ft/d. Vertical hydraulic conductivities range from a low of 7×10^{-4} ft/d in the Mahogany zone of the Parachute Creek Member to a maximum of 1.0 ft/d in some adjacent layers.

Infiltration of precipitation, primarily in areas with elevations greater than 7,000 ft, provides recharge to the aquifers in this closed ground-water basin. Ground water moves from the recharge areas along the eastern, southern, and western margins of the basin to the central and northern parts of the basin, where it discharges by evapotranspiration and surface flow in Yellow and Piceance Creeks. Total recharge and discharge in the basin was estimated to be about 32 ft^3/s, with the Piceance Creek drainage area receiving about 90 percent of the ground-water discharge and Yellow Creek drainage area receiving the remaining 10 percent. The flow of ground water through the basin is the result of a potentiometric gradient that is as steep as 130 ft/mi in some areas. The potentiometric head in the discharge area in the northern part of the basin is 1,600 ft lower than the potentiometric head in the recharge area 26 mi to the south. Potentiometric head differences as large as 240 ft occur between different depth intervals in the basin-aquifer system. In recharge areas away from major stream channels, the potential exists for downward movement of ground water, while near the major stream channels, the potential commonly exists for upward movement of ground water. These vertical head differences allow water recharging the near-surface layers of the aquifer to move to depth in the aquifer system and ultimately back to the surface near the stream valleys.

Marked differences in the dissolved-solids concentration are found in the ground water. Near the recharge areas, ground water with 400 to 800 mg/L of dissolved solids is common. In areas subject to upward movement of ground water from the northern part of the Parachute Creek Member, dissolved-solids concentrations range from about 2,000 to 45,000 mg/L. The source of the dissolved constituents, the direction of ground-water movement, and differing rates of dissolution combine to produce a complex water-quality distribution in the aquifers.

The two principal stratigraphic sources of dissolved solids found in ground water in Piceance basin are the saline zone and the Uinta Formation. The saline zone is a 340-mi^2 area located in the lower part of the Parachute Creek Member that contains nahcolite and halite. Ground water comes in contact with these soluble saline minerals primarily by moving through faults and joints penetrating this zone or by moving laterally between bedding layers into the edges of the saline zone. Through these two mechanisms the saline zone contributes about 1×10^5 lb/d of dissolved solids to the ground water. Infiltrating precipitation leaches salts from the unsaturated zone overlying the upper aquifer. This source of dissolution introduces about 9×10^4 lb/d of dissolved solids into the ground water of Piceance basin. The total salt load of the ground water is estimated to be 2×10^5 lb/d, of which 1.9×10^5 lb/d is supplied by the above sources. The remaining dissolved solids are produced by dissolution of soluble minerals contained in the water-bearing sediments in the basin.

Chemical reactions, in addition to dissolution, that are thought to be occurring in the basin aquifers include precipitation, ion exchange, and oxidation-reduction reactions. The product of the principal chemical reactions is a sodium bicarbonate water with oxidized sulfur species in the Uinta Formation and reduced sulfur species in the Parachute Creek Member. Carbonate species are produced primarily by reduction of sulfur species and dissolution of the carbonate minerals, calcite, dolomite, and nahcolite. Carbonate species are removed from the system in the northern part of the basin by calcite precipitation. Relatively large sodium concentrations are produced by ion exchange, and nahcolite and halite dissolution.

Trace constituents detected in ground water in significant concentrations include arsenic, barium, boron, fluoride, iron, lithium, and strontium. Lesser concentrations of beryllium, copper, cadmium, lead, mercury, manganese, molybdenum, selenium, and zinc were also detected. Primary evaporite minerals and primary and secondary sulfide minerals are the likely sources of the trace constituents found in the ground water.

A three-dimensional mathematical model was used to simulate the effects of mining activities on the water resources of the basin. The model simulates confined, density-dependent flow and solute transport with dispersion in nonhomogeneous, anisotropic aquifers under steady or transient flow conditions.

The model was calibrated by comparing the present-day potentiometric heads and dissolved-solids concentrations with model-calculated values. Model parameters, such as hydraulic conductivity, recharge rate, and dissolution rate were adjusted, within the constraints of the data, to improve the match between the measured and calculated values. An acceptable model calibration was achieved for steady-flow conditions. Calibration of transient-flow conditions was not possible, due to the lack of transient conditions in the basin.

The calibrated model was used to investigate the possible effects of in-situ mining activities requiring large-scale dewatering near the two Federal prototype-mine-lease tracts C-a and C-b. This dewatering could alter the direction of ground-water flow near the mines and consequently affect the chemical quality of the ground and surface water in the area.

The simulated mine in tract C-a was pumped at various rates and the model results indicated that: (1) Pumping the mine will decrease the dissolved-solids concentrations in ground water near the mine, and (2) increased pumping rates would further reduce the dissolved-solids concentrations in the lower aquifer.

The water-quality improvement would occur because the pumping would induce downward movement of better quality ground water into deeper zones containing poorer quality water. Downgradient from the mine, the dissolved-solids concentrations would increase due to the effects of the altered direction of ground-water movement near the mine. At a long-term pumping rate of 5 ft^3/s, the ground-water discharge to Yellow Creek valley would ultimately be reduced by about 2 ft^3/s, and discharge to Piceance Creek valley would be reduced by 3 ft^3/s. This reduction in flow would be accompanied by an 800-mg/L increase in dissolved-solids concentrations in part of Yellow Creek.

The simulated mine in tract C-b also was pumped at various rates. Model results indicate that as the mine-pumping rate was increased, the dissolved-solids concentrations near the mine would remain fairly constant in all but the deepest part of the lower aquifer. A decrease in dissolved-solids concentrations of as much as 1,100 mg/L would occur in the deepest part of the aquifer, if the mine were pumped at a rate of 15 ft^3/s. Downgradient from the mine, the dissolved-solids concentrations would increase by as much as 50 mg/L in a 90-mi^2 area. These concentration changes also would be due to a change in the direction of ground-water movement near the mine which would allow ground water of better quality to migrate into zones containing water of a poorer quality. If the mine were pumped at a long-term rate of 15 ft^3/s, the rate of ground-water discharge to Piceance Creek valley would be reduced by 15 ft^3/s. The resulting dissolved-solids concentration in the cumulative ground-water discharge would increase from 1,100 to 1,400 mg/L near the mouth of the creek.

Spent oil shale in abandoned mine retorts could contain large volumes of soluble saline minerals. From 30 to 150 million tons of saline minerals might be present in the spent shale remaining in a mine at the site proposed for tract C-b. Dissolution of these saline minerals through mine flooding could have a serious affect on the chemical quality of the ground- and surface-water resources of the Piceance basin.

Various operational procedures used in retorting the oil shale can affect the leaching rate of the minerals. The solute-transport model was used to simulate several mine-leaching rates in order to predict possible effects on the water quality in the basin. Model results for both tracts C-a and C-b indicate that the dissolved-solids concentrations in the aquifers increases with the rate and the duration of the leaching.

The aquifer zones with the largest hydraulic conductivity would have the largest increases in dissolved-solids concentrations, while the zones of smallest hydraulic conductivity would have the smallest increase in dissolved-solids concentrations. In tract C-a, a leaching rate of 1.3×10^5 lb/d would produce dissolved-solids concentrations near the mine in excess of 40,000 mg/L after 60 years of mine leaching. After 60 years of leaching, a 30-mi^2 area downgradient from the tract would have an increase in dissolved-solids concentrations in excess of 1,000 mg/L. Only minimal changes in water quality in Yellow Creek would occur after 60 years of leaching, primarily because ground water with relatively large dissolved-solids concentrations would not have reached the main areas of ground-water discharge along the creek.

Model simulations after 60 years of mine leaching in tract C-b indicate that dissolved-solids concentrations in excess of 20,000 mg/L would occur near the mine with a leaching rate of 1.3×10^5 lb/d. Under the same conditions, concentrations near tract C-a would be in excess of 40,000 mg/L. The discharge of ground water containing relatively large concentrations of dissolved solids into Piceance Creek near a leaching mine in tract C-b will adversely affect the water quality in the creek. Model results indicate that in a reach of Piceance Creek near tract C-b, dissolved-solids concentrations in cumulative ground-water discharge would increase from 750 mg/L to 1,750 mg/L after 60 years of leaching.

The model indicates that the ground-water quality near tract C-a will be more readily degraded by mine leachate than that near tract C-b. The area that would be affected by concentration increases in excess of 10 mg/L would be about 140 mi^2 near tract C-a and about 40 mi^2 near tract C-b. Equal rates of leaching of abandoned mines in tracts C-a and C-b will likely produce much different effects on the water resources of Piceance basin. Tract C-a, located away from perennial streams, primarily will affect the ground-water quality in a large area to the northeast of the tract. Tract C-b, in contrast, primarily will affect the surface-water quality in Piceance Creek, with only localized effects on the ground-water quality.

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